Appendix C

Mass Balance Modeling Analysis

LOWER EIGHT MILES OF THE LOWER PASSAIC RIVER
APPENDIX C: MASS BALANCE MODELING ANALYSIS

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1 INTRODUCTION

This appendix describes the Empirical Mass Balance (EMB) modeling analysis developed to support the Focused Feasibility Study (FFS) of the lower eight miles of the Lower Passaic River[1]. It encompasses sources to and receptors present in the tidal portion of the river, from River Mile (RM[2]) 0 to RM17.4, to provide a more complete understanding of contaminant fate and transport. The appendix is composed of the following chapters in addition to the introduction:

- *Chapter 2, Overview of the Fate and Transport Conceptual Analysis*: provides an overview of the contaminant fate and transport conceptual models.
- *Chapter 3, Empirical Mass Balance Model for the Lower Passaic River*: describes the EMB model established for the river, which is designed to characterize the fate and transport of contaminants in the Lower Passaic River.
- *Chapter 4, Empirical Mass Balance Model Results*: presents the results of the EMB for contaminants and solids.
- *Chapter 5, Forecasting Contaminant Concentrations*: presents the forecast concentrations of contaminants in Lower Passaic River surface sediment based on the EMB results.
- *Chapter 6, Summary*: summaries the results of the EMB and future forecast of contaminant concentrations.
- *Chapter 7, Acronyms*: defines the acronyms used in this appendix.
- *Chapter 8, References*: lists the references used in this appendix.

Appendix A (Data Evaluation Reports) and Appendix C (Mass Balance Modeling Analysis) contain elements previously discussed in the Draft Comprehensive Conceptual

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[1] Throughout this appendix, the term "Lower Passaic River" is used to refer to the tidal portion of the Passaic River, from Dundee Dam to the river mouth at Newark Bay (RM0 to RM17.4). The term "lower 8 miles" refers to the FFS Study Area, from RM0 to RM8.3. The term "Upper Passaic River refers to the freshwater portion of the Passaic River above Dundee Dam.

[2] The FFS uses the "River Mile" (RM) system developed by the United States Army Corps of Engineers (USACE), which follows the navigation channel of the Lower Passaic River. The Data Evaluation Reports (Appendix A), Empirical Mass Balance (Appendix C) and Lower Passaic River-Newark Bay model (Appendix B) were initially developed at the beginning of the 17-mile Remedial Investigation and Feasibility Study (RI/FS), and thus follow a RM system developed for that RI/FS, which follows the geographic centerline of the river. RM0 is defined by an imaginary line between two marker lighthouses at the confluence of the Lower Passaic River and Newark Bay: one in Essex County just offshore of Newark and the other in Hudson County just offshore of Kearny Point. River miles then continue upriver to the Dundee Dam (RM17.4). The two RM systems are about 0.2 miles apart.

Site Model (Malcolm Pirnie, 2008). A contractor-led independent peer review of this document was conducted from May 31 through July 7, 2008. As a result of this peer review several changes were made and were incorporated into Appendices A and C:

- A Monte Carlo technique was used to estimate uncertainty in the empirical mass balance and the prediction of future sediment concentrations under various remedial scenarios. The results were incorporated into Appendix C.
- Additional sampling events were conducted in 2008 to collect a set of low resolution cores above RM8 and a set of suspended solids samples from the CSOs and SWOs to address acknowledged data gaps. Also, in addition to the use of Monte Carlo analysis to estimate uncertainties, the discussion of the high resolution core dating assignments was expanded and refined. The results were incorporated into Appendices A and C.

2 OVERVIEW OF THE FATE AND TRANSPORT ANALYSIS

For the FFS, two separate model-based examinations of contaminant transport were conducted. This Appendix presents one of these examinations, called the EMB Model, which used an empirical receptor modeling approach to simultaneously examine the particle-borne concentrations of a broad suite of contaminants and other compounds to establish the magnitude of each contaminant contribution from each of the major sources to the estuary. Appendix B[3] presents the other examination, the Lower Passaic River-Newark Bay Model, which used a mechanistic modeling approach, incorporating hydrodynamic and sediment transport modeling results while modeling various contaminants on an individual basis.

In this Appendix, the goal of the modeling was to infer contaminant contributions from various sources, and to use this result to empirically forecast future concentrations under different remedial alternatives. To do this for the Lower Passaic River, a "receptor" modeling approach was undertaken. Receptor models are empirically-based, focus on the behavior at the receptor site, and infer contributions from different sources based on multivariate measurements taken at the receptor site and likely sources.

Receptor models have been widely used in the field of air pollution [*e.g.*, United States Environmental Protection Agency (USEPA) Chemical Mass Balance (CMB) Model (Watson *et al.*, 2004)] as tools for identification of pollutant sources and evaluation of their relative contributions. Recently, receptor models have also been applied to sediment sites that are contaminated with polychlorinated biphenyl (PCB), polychlorinated dibenzodioxin/furan (PCDD/F), and polycyclic aromatic hydrocarbon (PAH) compounds. Examples of these sediment contamination sites include: the Fox River in Wisconsin (Su *et al.*, 2000), San Francisco Bay in California (Johnson *et al.*, 2000), the Ashtabula River in Ohio (Imamoglu *et al.*, 2002), Lake Calumet in Chicago (Bzdusek *et al.*, 2004), and Tokyo Bay and Lake Shinji in Japan (Ogura *et al.*, 2005). The objectives of the receptor

[3] This appendix makes extensive use of cross references to direct the reader to the sources of the analyses and conclusions incorporated in this appendix.

model are to determine the number of sources contributing to the system, the contaminant composition of each source, and the relative contribution of each source to the receptor site.

For the FFS, the receptor model described here will focus on explaining the contaminant concentrations in recently-deposited sediments [*i.e.*, Beryllium-7 (Be-7)[4] -bearing sediment] in the Lower Passaic River. Recently-deposited sediments integrate the various sources to the Lower Passaic River water column, as well as internal river processes that affected these sediments when they were deposited during the prior six to twelve month period. Because the source compositions are known and data are available to determine their contaminant composition, the non-negative constrained contaminant mass balance approach is used. This approach used in the analysis follows a recent application of the USEPA CMB model that was combined with Monte Carlo techniques[5], to account for uncertainty and variability in the data (Ogura *et al.*, 2005). A detailed description of the Monte Carlo analysis methodology and how it was used to account for uncertainties in source and receptor compositions is given in Attachment A.

The following sections describe the empirical modeling analyses that were incorporated in the development of the Conceptual Site Model (CSM) to gain insight into some of the important environmental processes occurring in the Lower Passaic River. The analyses performed included: Contaminant Mass Balance for the Lower Passaic River and Development of a Mass Balance Forecast Model to forecast contaminant concentrations for the Lower Passaic River.

[4] Be-7 is a naturally occurring, particle-reactive radioisotope with a short half-life (53 days). The presence of Be-7 in surface sediments suggests that the associated solids were deposited on the sediment bed within the last 6 months (termed "recently-deposited surface sediments") prior to collection.
[5] Monte Carlo is an analytical technique where a large number of simulations are run, using randomly selected quantities from a specified distribution for each variable, and the output then reviewed and evaluated to determine which values are the most likely. In this Monte Carlo simulation, the concentrations of contaminants in the sources and receptor are generated randomly from defined distributions, and the mass balance calculation is repeated many times with different randomly determined data to allow statistical conclusions to be drawn.

2.1 Contaminant Mass Balance Considerations for the Lower Passaic River

Contaminants are transmitted through the environment by a variety of processes, including advection and dispersion, as both dissolved constituents and adsorbed constituents of particles. The contaminants themselves also undergo alterations due to environmental processes such as adsorption to and desorption from particles and degradation through microbial respiration. Contaminant fate and transport analysis attempts to understand the effects of these processes either through mechanistic or empirical means. For the FFS, both means were used to provide two lines of evidence on which to base decisions. The mechanistic contaminant fate and transport model is presented in Appendix B. The EMB model, a semi-empirical formulation presented here, evaluates the relative contributions of the important boundary conditions [the Upper Passaic River, Newark Bay, tributaries, Combined Sewer Overflows/Stormwater Outfalls (CSOs/SWOs) and resuspended legacy sediment acting as sources to the recently depositing sediments (*i.e.,* Be-7-bearing sediment)]. Note that the term "resuspension of legacy sediment" represents all the net sediment transfer processes from the bed of the Lower Passaic River that will affect recently-deposited sediment, including: resuspension, porewater exchange, and bioturbation. The EMB model for the Lower Passaic River is developed in Chapter 3, with results and conclusions provided in Chapter 4.

The following tasks were conducted to prepare and solve the EMB model:

- A contaminant mass balance equation was developed to determine the relative contribution of each external source of fine-grained solids and associated contaminants (Upper Passaic River, tributaries, CSOs/SWOs, and Newark Bay) to the recently-deposited (Be-7-bearing) sediments of the Lower Passaic River.
- An empirically-based receptor model was selected to solve the mass balance equations for the relative contributions of the known sources to the receptor. The model combines a non-negative constrained contaminant mass balance with sensitivity analysis simulations to address variability and uncertainty in the source characterizations.

- The solids contribution from the tributaries and point discharges were further constrained using their watershed areas to ensure that their model-estimated solids contributions do not exceed their watershed solids carrying capacity.
- Contaminant parameters from the available datasets were subjected to a cluster analysis to identify independent contaminants that were uniquely associated with the sources. The Lower Passaic River accumulates solids that originate from several sources. In order for the EMB model to decipher the contribution of these sources to the receptor sediments, independent parameters must be identified and applied in the model. Independent parameters are contaminants that have independent sources, or different fate and transport processes, or both. The combination of contaminants selected for analysis must provide a unique pattern for each of the various sources in order for a unique solution to be obtained by the model.
- A total of 22 parameters were used in the model. Of these, 13 were directly used in model optimization to determine the solids contributions. The remaining nine were used to further evaluate the model performance.
- Model performance was evaluated using a normalized mean error defined as the difference between the predicted and the observed, normalized to the observed receptor concentration for each parameter.
- Uncertainties in source and receptor composition and spatial variability in contaminant concentrations were accounted for through a Monte Carlo analysis.

2.2 Forecasting Contaminant Concentrations in Surface Sediments

Using the results of the EMB model, a two-layer single box model was developed for use in forecasting Lower Passaic River contaminant concentrations in sediment. This is described in Chapter 5. The average surface concentrations for various contaminants in the 0 to 6 inch sediment layer of the Lower Passaic River were empirically forecast under the four remedial alternatives being evaluated in the FFS using a numerical model combined with a stochastic simulation. The forecasting formulation aggregates the river section between RM2 to RM12 as a two-layer single box model consisting of a water column where mixing of particles from external sources and resuspension occurs, and a mixed-layer surface sediment bed to which particle deposition from the water column occurs. The rationale for using the single aggregate representation of this river section follows from observations of recently-deposited sediments which show little longitudinal variation in concentrations from RM2 to RM12 (see Data Evaluation Report No. 4 in Appendix A). Note that there are concentration gradients at either end of this river section representing mixing zones with Upper Passaic River solids (*i.e.*, from RM12 to RM17.4) and Newark Bay solids (from RM0 to RM2), each with relatively low contaminant concentrations. Furthermore, although the 1995 Tierra Solutions (TSI) surface sediment data (see Data Evaluation Report No. 1 in Appendix A) indicate significant spatial variability in surface contaminant concentrations in the river, this variability (as well as other sources of variability) were accounted for stochastically by a Monte Carlo simulation approach, providing an estimate of the distribution of future contaminant concentrations in the river bed. The forecasting analysis integrated results from the EMB model (Section 3.0), observed surface sediment concentrations (Data Evaluation Report No. 4 in Appendix A), current contaminant compositions of external sources (Data Evaluation Report No. 2 in Appendix A), and historical trends of contamination from dated sediment cores (Data Evaluation Report No. 3 in Appendix A).

3 EMPIRICAL MASS BALANCE FOR THE LOWER PASSAIC RIVER

3.1 General Summary of Model

Understanding the various contaminant inputs to the river is essential to determining the effectiveness of remedial strategies. For this reason, it is necessary to establish the importance of each potential source of contaminants to the Lower Passaic River. The EMB model was developed to estimate the magnitude of the tributaries, CSOs/SWOs, Newark Bay, and Upper Passaic River as contaminant sources relative to the resuspension of legacy sediments and their associated contaminant inventory (Figure 3-1), in order to aid decision-making regarding the remedial alternatives being evaluated in the FFS.

As part of the process to evaluate alternatives, the FFS requires an estimation of the post-remediation contaminant concentrations for each alternative. The FFS also requires an estimation of the potential risk from exposure to these future contaminant concentrations. Before post-remediation surface sediment concentrations can be predicted, the current conditions in the river must be understood and the relative contaminant burden currently delivered from each source to the Lower Passaic River must be quantified. As shown on Figure 3-1, the recently-deposited sediment concentrations in the Lower Passaic River are derived from some combination of several sources, which can be represented with the following contaminant mass balance equation for each contaminant (i) (Equation 3-1):

$$C^{i}_{surface} = \frac{M^{i}_{DD} + M^{i}_{NB} + M^{i}_{SR} + M^{i}_{3R} + M^{i}_{2R/SWO} + M^{i}_{CSO} + M^{i}_{RSP}}{S_{total}} \qquad \text{Equation 3-1}$$

Where

$C^{i}_{surface}$: contaminant i concentration in the Lower Passaic River surface sediments

M^i_{DD}: contaminant i mass derived from the Upper Passaic River (The subscript DD is a reference to the Dundee Dam, the structure that divides the Lower and Upper Passaic Rivers.)

M^i_{NB}: contaminant i mass derived from Newark Bay

M^i_{SR}: contaminant i mass derived from Saddle River

M^i_{3R}: contaminant i mass derived from Third River

$M^i_{2R/SWO}$: contaminant i mass derived from Second River and the SWOs

M^i_{CSO}: contaminant i mass derived from the CSOs

M^i_{RSP}: contaminant i mass derived from sediment resuspension

S_{Total}: total sediment mass load deposited in the Lower Passaic River

Note that the phrasing "derived from" indicates that the mass contribution comes from a specific source, but not all of the mass delivered by these sources is deposited on the surface of the sediment bed of the Lower Passaic River. Equation 3-1 represents the recently-deposited surface sediments of the Lower Passaic River as a combination of the solids and contaminant mass originating from various sources. Based on this contaminant mass balance, a receptor[6]-type model was developed where the total contaminant mass present in the sediments of the receptor (*i.e.*, the recently-deposited, Be-7-bearing sediments in the Lower Passaic River) is the sum of the mass contributions from the individual sources. For a fixed number of sources (p), the receptor observation of the i^{th} contaminant ($i = 1, 2 \ldots, j$) is modeled as a linear combination of sources' contaminant species as presented in Equation 3-2. (Equation 3-2 is an algebraic manipulation of Equation 3-1 where the contaminant mass from each source is represented by a concentration and a solids fraction.)

$$Y_i = \sum_{j=1}^{p} f_j X_{ij} + \varepsilon_i \qquad \text{Equation 3-2}$$

[6] The term "receptor" is used throughout Chapter 3 of this appendix to refer to the concentrations in sediments depositing on the river bottom (*i.e.*, recently -deposited sediments). This receptor represents the integration of the various external and internal loads. This term is not the same as the risk assessment definition of the term, as used elsewhere in the FFS.

Where

Y_i: receptor concentration for the i^{th} contaminant concentration

X_{ij}: the i^{th} contaminant concentration for the j^{th} source

f_i: fraction of solids contributed by the j^{th} source to the receptor

e_i: error associated with the concentration of the i^{th} contaminant

p: number of sources

Note that the term f_i represents the fraction of solids by the i^{th} source to the Be-7-bearing sediments (*i.e.*, the receptor). Given that there are seven possible sources, there are then seven f_i terms. The regression process solves for these seven f_i terms by optimizing the f_i values and minimizing the residual error term e_i. The EMB model is designed to be solved simultaneously for the contaminant burden of the i^{th} contaminant species for each j^{th} source, assuming that the model parameters are independent. The following premises were considered in the design of the EMB model:

- The number of sources is known and includes the Upper Passaic River (above Dundee Dam), Saddle River, Third River, Second River, CSOs, SWOs, resuspension of legacy sediments within the Lower Passaic River, and Newark Bay. Contaminant inputs from atmospheric deposition and groundwater have been determined to be negligible [See Data Evaluation Report No. 2 in Appendix A].
- Because the SWO samples were collected from points below the high-tide mark, solids collected from the SWOs represent a mixture of river-originated solids and SWO-originated solids. Since the data from the SWO samples were compromised by the intrusion of Lower Passaic River sediments into the SWOs, the contribution from Second River and the SWOs was combined as a single term in the model and the contaminant characteristics of both were based on samples taken in Second River (see Data Evaluation Report No. 2 in Appendix A for a discussion of SWO data quality). Second River was deemed to be representative of SWO discharges into the Passaic River, because the Second River drains a highly-urbanized watershed that is fed primarily by storm water collection systems. A sensitivity analysis simulation was conducted to evaluate the impact of the SWO concentrations on model results.

- The nature of the sources is known, and the available data represents the current average composition of all these sources. In most instances, those sources are characterized by samples collected at or near their discharge points to the Lower Passaic River. The source characteristics for resuspension of Lower Passaic River sediments were represented by the surface concentrations from the 1995 TSI dataset. The 1995 TSI dataset is considered representative of the contaminant signature of the net transfer of sediment from the bed to the water column through mechanisms such as erosion, bioturbation, and other resuspension processes. Although the surface sediment concentration in the 1995 TSI data sets were used to define the resuspension signature for the EMB model, this analysis does not assume that erosion is limited to the surface sediments only. The concentrations of most of the contaminants analyzed in the EMB model vary by several orders of magnitude in the 1995 TSI surface sediment data (see Data Evaluation Report No 4 in Appendix A). For example, surface concentrations of 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) vary by four orders of magnitude (see Data Evaluation Report No. 4 in Appendix A). This variability likely represents the range of concentrations of sediments that are resuspended into the water column, which is incorporated into the EMB model through a Monte Carlo analysis. Note that median surface sediment contaminant concentrations have not changed much between 1995 to 2012 (see Temporal and Spatial Trends sections of Data Evaluation Report No. 4 in Appendix A). Furthermore, the 1995 Remedial Investigation (RI) program was designed to follow a systematic (*i.e.,* unbiased) sampling scheme. Sediment cores were collected from multiple transects spaced at quarter mile intervals, with three cores along each transect (see Figure 2.1-1 of Data Evaluation Report No. 4 in Appendix A).

- The model focuses on the movement of solids; therefore, it tracks the contaminant species associated with the solids. Since the modeled compounds are primarily hydrophobic contaminants, dissolved-phase concentrations (and the processes impacting dissolved-phase concentrations) are relatively small and are not addressed by the model.

- The contaminant species included in the mass balance do not react with each other and can be added linearly.
- The EMB model system is over-determined [there are 13 parameters (twelve contaminants plus Total Organic Carbon (TOC), see Table 3-1) and 7 equations], meaning that the number of sources is less than or equal to the number of contaminant species. Because it is over-determined, several physical constraints were applied to guide the model solution (see sections 3.2.1, 3.5, and 4.4).
- The source profiles [*i.e.,* the relative proportion of the 13 parameters (see Table 3-1) in each source] are linearly independent of each other, and any contaminant transformations or losses that occur between the source and receptor are not considered. Only contaminants that aid in differentiating among the sources (*i.e.*, make the sources independent) were selected for the modeling analysis.
- Uncertainties in the measurement of contaminants and spatial variability are addressed through a Monte Carlo simulation approach.

Once the receptor solids and source solids were characterized, statistically independent parameters were identified (see Section 3.3) and the average concentrations of these parameters were used as inputs to the EMB model. The output of the EMB model quantifies the relative contribution of the contaminant burden and solids load from each source to the recently-deposited (Be-7-bearing) Lower Passaic River sediment. The fate and transport implications of the model output were then described qualitatively for each contaminant. This modeling approach, which was used to describe the contaminant burden of the river under current conditions, was also used to provide insight to the application of the mechanistic model described in Appendix B.

3.2 Model Formation

3.2.1 Function and Constraints / Assumptions and Limitations

The receptor model was formulated following the principles described in Section 3.1 and using Equations 3-1 and Equation 3-2. The linear equations generated from Equation 3-2 were solved simultaneously using a least square solution to determine the fraction of the contaminant burden (*i.e.,* the contaminant flux) contributed by each source to the Lower Passaic River. This solution was achieved by establishing an objective function as defined by Soonthornnonda and Christensen (2008) below (Equation 3-3):

$$Q^2 = \sum_{i=1}^{n} \left[\frac{\left(Y_i - \sum_{j=1}^{p} f_j X_{ij} \right)^2}{(r.e._k Y_i)^2 + \sum_{j=1}^{p} \left\{ f_j (r.e._i X_{ij}) \right\}^2} \right] \quad \text{Equation 3-3}$$

Where:

Q^2:	weighted sum of squares differences between predicted and observed receptor concentrations
Y_i:	concentration in Lower Passaic River surface sediment for the i^{th} contaminant
f_j:	fraction of solids contributed by the j^{th} source to the Lower Passaic River
X_{ij}:	i^{th} contaminant concentration from the j^{th} source
p:	number of sources
n:	number of contaminant species (assuming that $n > p$)
$r.e._k$:	relative error or uncertainty and spatial variability in Y_i.
$r.e._i$:	relative error or uncertainty and spatial variability in X_{ij}.

To optimize the f_j values, the objective is to choose the f_j values so as to minimize the value of Q^2. According to Soonthornnonda and Christensen (2008), these relative errors can be characterized by the standard error of the measurements for each contaminant and Equation 3-3 reduces to an expression used by Ogura et al., (2005) given by:

$$Q^2 = \sum_{i=1}^{n} \left[\frac{1}{\sigma_i} \left(Y_i - \sum_{j=1}^{p} f_j X_{ij} \right) \right]^2 \quad \text{Equation 3-4}$$

Where:

σ_i: uncertainty and spatial variability determined by the standard error in contaminant concentrations.

Consistent with Ogura et al., (2005), the uncertainty or standard error term σ_i in this analysis is replaced by Y_i itself in the objective function because the magnitude of the variability was found to depend on the magnitude of the detected concentration (Figure 3-2). Dioxins/Furans, which have the smallest concentrations, have the smallest standard errors, while the heavy metals, which have the highest concentrations, have the highest standard errors. Without consideration of these differences, the chemicals with the largest variability will dominate the calculation.

The solution of the objective function (Equation 3-4) was limited by the following constraints:

- The sum of the solids fractions contributed by each source (f_j) equals one. (This constraint was tested in a sensitivity analysis on the model solution.)
- Non-negativity constraint is applied to ensure that a source cannot have a negative contribution: $f_j \geq 0$ (*i.e.*, no source can subtract contamination from the Lower Passaic River sediments).
- A watershed delivery constraint is applied to avoid solids contribution results from the least squares equation that are unrealistic with regard to the delivery capacity of the sources. These constraints were written for the inputs from tributaries (Saddle River, Second River/SWOs, and Third River) and CSOs as limiting linear functions of contribution from the Upper Passaic River using a tolerance of ±50 percent of the watershed area ratios according to Equation 3-4 (see Table 5-1 in Data Evaluation Report No. 2 in Appendix A for watershed areas). Note that the mass balance is not contingent on the absolute magnitude of the solids load or watershed area but only on the relative proportions of each source. The watershed delivery constraints are expressed as a fraction of the solids load delivered by the Upper Passaic River as follows:

$$0.037 \le \frac{S_{Saddle\_River}}{S_{Upper\ Passaic\ River}} \le 0.111 \qquad \text{Equation 3-4a}$$

$$0.008 \le \frac{S_{Third\_River}}{S_{Upper\ Passaic\ River}} \le 0.024 \qquad \text{Equation 3-4b}$$

$$0.020 \le \frac{S_{Second\_River/SWO}}{S_{Upper\ Passaic\ River}} \le 0.061 \qquad \text{Equation 3-4c}$$

$$0.015 \le \frac{S_{CSO}}{S_{Upper\ Passaic\ River}} \le 0.046 \qquad \text{Equation 3-4d}$$

Where

S_{Saddle_River}:	solids load from the Saddle River
S_{Third_River}:	solids load from the Third River
$S_{Second\_River/SWO}$:	solids load from the Second River and SWOs
S_{CSO}:	solids load from CSOs
$S_{Upper\ Passaic\ River}$:	solids load from the Upper Passaic River

The EMB model calculations were performed using a combination of Microsoft Excel® Solver and the Crystal Ball® 7 (Decisioneering, Denver, CO, USA) add-on for Microsoft Excel® (a tool typically used for solving optimization problems). Using the model formulation described above, a best estimate solution was obtained based on the average source and receptor concentrations. A Monte Carlo analysis consisting of 10,000 iterations of randomly generated source and receptor contaminant concentrations was performed to assess the impact of variability and uncertainty in source and receptor concentrations on the best estimate solution. Finally, sensitivity analysis simulations were conducted to evaluate the impact of the SWO concentrations and the model solids constraint on the best estimate model solution. The model best estimate solution was assessed using model performance criteria (described below).

3.3 Identifying Contaminants for Inclusion in EMB Model

The Lower Passaic River accumulates solids that originate from several sources. In order for the EMB model to decipher the contribution of these sources to the receptor sediments, independent parameters must be identified and applied in the model. Independent parameters are contaminants that have independent sources and/or different fate and transport processes. Note that in the special case where a contaminant is not independent of another contaminant, but together they form a fingerprint that can be used to distinguish the sources, the two contaminants can be considered in the analysis. The combination of contaminants selected for analysis must provide a relatively unique pattern for each of the various sources in order for a unique solution to be obtained by the model. Contaminants were selected from each of the compound classes, including: dioxins/furans, PCBs, PAHs, pesticides, and metals. The individual contaminants chosen are as follows:

- For dioxin/furan compounds, 2,3,7,8-TCDD and total tetrachlorodibenzodioxin (Total TCDD) were selected. Although they are not independent parameters, both were included because their ratio is an important tracer for Lower Passaic River solids throughout the New York-New Jersey Harbor Estuary (Chaky, 2003).
- For PCBs, the data for the external sources were reported on a congener basis. However, because the TSI 1995 data was reported on an Aroclor basis, the sum of PCB Aroclors was selected to represent PCBs.
- For PAHs, the contaminants were selected based on the results of cluster analysis performed on PAH mass fractions. Clustering is the partitioning of a dataset into subsets, or “clusters,” where the data in each subset share some common trait. The PAH cluster analysis yielded three different clusters (Figure 3-3). The two independent PAHs selected from two of the clusters as contaminants with unique sources or fate and transport processes consist of Benzo(a)pyrene (from the green group in Figure 3-3) and Fluoranthene (from the blue group in Figure 3-3). The third cluster was not included because it contained mostly 2- and 3-ring PAH compounds, which likely have significant dissolved phase concentrations and may

not be conservative particle tracers. Note that the EMB model focuses on particle-bound contaminants.

- For pesticides, the selected compounds were limited by data availability and difference in analytical techniques. In the TSI 1995 data set only Total DDx[7] compounds were reported for the DDT group of compounds. In Newark Bay, only dichlorodiphenyldichloroethylene (DDE) was consistently detected in the sediments. Therefore, 4,4'-dichlorodiphenyldichloroethylene (4,4'-DDE) was selected for the EMB model. In addition, gamma-Chlordane was selected because dated sediment cores indicated that there has been little or no change in sediment concentration over time and thus provides a good check on the model (See Data Evaluation Report No. 3 in Appendix A).
- For the metals, cluster analysis was used to separate them into four different clusters (Figure 3-4). Four metals were selected (chromium, copper, lead and mercury), one from each cluster, as contaminants with unique sources or fate and transport processes.

In addition to the above contaminants, the contaminant normalizers iron and TOC were included to account for variability in particle size and organic carbon content of the sediment. These normalizers helped to reduce the variability in the concentrations of sediments and suspended solids (see Data Evaluation Report No. 4 in Appendix A).

The EMB model was designed to solve simultaneous mass balance equations for various parameters by optimization. Thirteen parameters (eleven contaminants plus iron and TOC) were directly used in the model for optimization (Table 3-1).

In addition to the list of 13 optimized parameters, another nine parameters were selected for further EMB model evaluation (Table 3-2). This additional EMB model evaluation was done by: 1) using model-optimized solids contributions to predict the concentrations of the nine additional parameters in recently-deposited sediment of the Lower Passaic

[7] Total DDx refers the sum of the 4,4'-dichlorodiphenyldichloroethane (4-4'-DDD), 4,4'-dichlorodiphenyldichloroethylene (4,4'-DDE) and 4,4'- Dichlorodiphenyltrichloroethane (4,4'-DDT) concentrations in a sample.

River, and 2) comparing the predicted concentrations to the observed values for these parameters.

3.4 Best Estimate Scenario

The sources and the receptor used in the EMB model are shown in Figure 3-1. For completeness, a brief description of each source and the receptor is provided here along with their respective concentrations used for the model parameters. The concentrations of these parameters represent the best estimates for the various sources/receptor; the application of these concentrations in the EMB model is called the best estimate scenario.

- Resuspension of the FFS Study Area legacy sediments was represented by the average surface concentrations from the 1995 TSI dataset (*i.e.,* 0-6 inches surface sediment from RM1 to RM7). The average contaminant concentrations for the resuspension signature are summarized in Table 3-3.
- Newark Bay was characterized by a northern and southern region. Average contaminant concentrations for these regions are shown in Table 3-4; however, the Newark Bay end member is represented by the northern region in the base case simulation given its proximity to the Lower Passaic River. The surface sediment (0-6 inch) samples used to delineate the Newark Bay end member were from the 2005 Phase 1 and 2007 Phase 2 RI study by TSI. Only surface sediments (0-6 inches) at depositional locations in the channel were considered (see Data Evaluation Report No. 2 in Appendix A for discussion).
- The Upper Passaic River was characterized by four Be-7-bearing surface sediment samples (only two of these were analyzed for organic contaminants), four Be-7-bearing dated sediment core tops, and the suspended solids from two sediment traps. These samples were collected between 2005 and 2008. The average contaminant concentrations for the Upper Passaic River are summarized in Table 3-5.
- Tributary concentrations were based on averages from several recently-deposited surface sediment samples and sediment trap samples obtained during the 2007/2008 sampling event. The average contaminant concentrations for the tributaries are summarized in Table 3-6. Water column suspended sediment samples were removed

from the population before the calculation of the statistics because these water column samples represent a snap-shot at the time of collection (a few hours), and may not be representative of average conditions. Indeed, several of them were reported to have unusually high concentrations of many of the contaminants (possibly reflecting rain event-driven peaks in contaminant concentrations). The exception is Second River, where sediment and water column suspended sediment samples were used. These water column suspended sediment samples did not show the variability observed in other surface water samples and there were not enough sediment samples to calculate meaningful statistics from sediment alone.

- The CSO and SWO data were based on water column suspended sediment samples taken at the outfalls of several CSO and SWO locations (Table 3-7). The SWO samples were determined not to be representative of the contribution of SWOs to the contaminant loads in the river and they were not used in the base case model simulation (see Section 3.2 for a discussion of the data quality from the SWO samples).
- The recently-deposited Lower Passaic River surface sediments are the receptor in the model. They were characterized by recently-deposited sediments, including core tops from the 2005 high resolution cores and Be-7 surface sediment samples from the 2007/2008 sampling event. Data Evaluation Report No. 4 in Appendix A shows that most contaminants have relatively constant iron-normalized concentrations from RM2 to RM12, but these ratios often vary at the two ends of the study area. For this reason, only data for samples between RM2 and RM12 were used in the model. The average concentrations are listed in Table 3-8.

3.5 Sensitivity Analysis of SWO Concentrations and Solids Constraint

The base estimate scenario described above used the best estimates of the concentrations for the various parameters for the sources/receptor in the EMB model. However, because the SWOs were not sampled at a location above the influence of the Lower Passaic River, the data from the SWO samples were compromised by the intrusion of Lower Passaic River sediments into the SWOs. Therefore, the contributions from Second River and the SWOs were combined in the model and the contaminant characteristics of both were based on samples taken in Second River only (see Section 3.2 for a discussion of SWO data quality). The Second River was deemed to be representative of SWO discharges into the Passaic River, because the Second River drains a highly-urbanized watershed that is fed primarily by storm water collection systems. To assess the impact of this premise on the best estimate solution, a model scenario was conducted that separated the SWO from the Second River, with the SWO contaminant profile represented by the average of the compromised SWO data. The solids and contaminant contributions obtained from this sensitivity scenario were compared with the corresponding results from the best estimate solution.

The second sensitivity analysis performed was to assess the impact of the solids constraint on the best estimate solution. The solids constraint states that the sum of the solids fractions from the various sources in the objective function (Equation 3-4) equals one. Because of differences in the particle size distribution from the various sources, the sum of the solids fractions may not necessarily be equal to one. This constraint was tested in a sensitivity analysis and the model solution was compared to the results for the best estimate scenario.

3.6 Monte Carlo Analysis of Uncertainty and Variability in Contaminant Concentrations

The best estimate scenario described above used the best estimates of the concentrations for the various parameters for the sources and receptor in the EMB model; however to account for uncertainties and variability in source and receptor compositions, a Monte Carlo sampling approach was used to develop 10,000 iterations of the input parameters and the EMB model was optimized for each set of input parameters (*i.e.*, 10,000 optimized solutions were obtained). The objective of the Monte Carlo analysis was to develop confidence bounds in the EMB model-estimated solids balance and contaminant fate and transport deduced from the solids balance by accounting for uncertainties in source and receptor composition, and in the spatial variability in parameter concentrations. Detailed description of the Monte Carlo simulation approach is given in

Attachment A. In brief, the Monte Carlo simulation approach was used to develop the 10,000 iterations of the input parameters as follows:

- For the external sources and the receptor concentrations, a bounded normal distribution defined by the mean, standard deviation, minimum, and maximum of each parameter in each source term and receptor was used to perform the Monte Carlo simulation.
- For resuspension, a bootstrap[8] method was used to simulate the 10,000 iterations of the contaminant concentrations in resuspended sediment since the 1995 TSI data are neither normal nor log-normal.
- The correlations amongst the parameters for each source and receptor were examined to verify that the 10,000 iterations of parameter profiles represent the contaminant inter-dependencies.

As stated previously, 10,000 iterations were used to create 10,000 optimized model estimates of the solids concentrations. Those 10,000 estimates of the solids contributions were used to developed confidence levels of the solids contribution and the sources parameter contributions to the Lower Passaic River.

3.7 Model Performance Evaluation

Model-optimized receptor concentrations for the 13 optimized parameters and model-predicted receptor concentrations for the nine additional contaminants were evaluated for the best estimate scenario using a statistical indicator called the normalized mean error (NME). The NME is defined as the difference between the predicted and the observed, normalized to the observed receptor concentration for each parameter (Equation 3-5):

$$NME = \frac{C_{model} - C_{measured}}{C_{measured}} \qquad \text{Equation 3-5}$$

[8] Bootstrap is a powerful Monte Carlo method that re-samples the original sample set with replacement to generate a distribution of sample's statistics. It is a non-parametric method.

where,

C_{model}	=	Parameter-specific concentration estimated by the model
$C_{measured}$	=	Parameter-specific concentrations measured in the Lower Passaic River

The NME expresses the bias in model predictions and observations, and gives an indication of overestimation (NME >0) or underestimation (NME <0) for each contaminant.

3.8 Model Limitation

Receptor models are inferential in nature, meaning that they infer the contributions from different sources based on multivariate measurements collected at the receptor site. Because the models infer rather than predict, they cannot be used directly to estimate future changes in the system under certain conditions. For example, while the model indicates that a fraction of the Lower Passaic River bottom sediments is composed of Newark Bay sediments, the model cannot predict how the Newark Bay contribution will change after the Newark Bay channel is deepened.

4 MODELING RESULTS

This chapter discusses the EMB model solids balance results and the fate and transport of contaminants deduced from the solids balance in the Lower Passaic River. The EMB model calculations were performed for the best estimate scenario and a Monte Carlo analysis was included to assess the uncertainty in model estimates. In addition, two sensitivity analysis scenarios were performed to assess the sensitivity of the model result to the inclusion of compromised SWO sample results and to the use of tributary solids constraints included in the model. The model results for the best estimate scenario form the basis for the solids balance and contaminant fate and transport in the river. The results of the Monte Carlo analysis were used to account for uncertainties and spatial variability on the best estimate model results, and these uncertainties were expressed as confidence levels on the best estimate solution. The Monte Carlo analysis also provided a median estimate based on the 10,000 iterations which was also compared to the best estimate scenario.

4.1 EMB Model Solids Balance Results: Best Estimate Scenario and Uncertainty

Thirteen parameters [Table 3-1; copper, chromium, mercury, lead, gamma-Chlordane, 4,4'-DDE, 2,3,7,8 TCDD, Total TCDD, Total PCB, benzo(a)pyrene, fluoranthene, iron, and TOC] were optimized in the model to determine the solids balance. The model was then used to predict the receptor concentrations for the remaining nine parameters in Table 3-2 to evaluate its performance (see Section 4.3 below). Note that while iron and TOC are not contaminants, they are generally important in the transport of fine particles and associated contaminants. In particular, the inclusion of iron and TOC in the EMB model is an indirect means of normalizing the various source terms to their fine-grained sediment content. Therefore, the EMB model focuses on those sediments that contain and transport the majority of the contaminant burden.

Uncertainties in the model solution were developed from the Monte Carlo analysis based on confidence intervals (5^{th} and 95^{th} percentiles) of the 10,000 optimized solutions. The results of the EMB model optimization of the 10,000 Monte Carlo iterations are presented later in this discussion as box and whisker plots which depict the median solution plus the 5th, 25th, 75th and 95th percentiles of the 10,000 iterations. The best estimate solution was also added to the plots.

The EMB model solids balance results are shown in Figure 4-1 based on best estimates of the concentrations of contaminants. The best estimate solution indicates that resuspended solids account for about 48 percent of the total solids in recently-deposited (Be-7-bearing) sediments in the Lower Passaic River. Newark Bay and the Upper Passaic River account for about 14 percent and 32 percent, respectively, of the solids delivered to the Lower Passaic River. The tributaries, CSO and SWO together contribute about 6 percent of the solids. Uncertainties in these solids fraction estimates derived from the Monte Carlo iterations (Figure 4-2) indicate that resuspension accounted for about 28 to 65 percent, Upper Passaic River accounted for about 13 to 49 percent, Newark Bay accounted for less than 1 to 44 percent, and all the other sources together contribute between 2 and less than 12 percent. The relatively high contribution of solids from resuspension translates to a high resuspension contribution (33 percent or higher) of the contaminant burden (Table 4-1) in recently-deposited (Be-7-bearing) sediments.

4.2 EMB Model Contaminant Fate and Transport

The EMB model solids balance results presented above (Section 4.1) lead to further discussion of the fate and transport of contaminants in the Lower Passaic River. The fate and transport discussions are based on the mass balance outputs showing the distribution of the contaminant flux among the sources and a comparison of average contaminant concentrations used to characterize each source. This section is divided into two sub-sections: (1) fate and transport of parameters examined and optimized in the EMB model, and (2) inferred fate and transport of additional parameters. The results for the best estimate scenario and the associated Monte Carlo-based uncertainty are presented for the contaminants examined in the EMB model. Only the best estimate scenario is presented for fate and transport of additional contaminants, since these contaminants were not part of the Monte Carlo analysis.

4.2.1 Fate and Transport of Contaminants Optimized in the EMB Model

2,3,7,8-TCDD and Total TCDD Mass Balances

The upper panel of Figure 4-3a presents a box and whisker plot of the 2,3,7,8-TCDD concentration for each source with a solid line (marked "Target Concentration[9]") representing the average 2,3,7,8-TCDD concentration in recently-deposited (Be-7-bearing) sediments in the Lower Passaic River (from RM2 to RM12). The first striking feature is that external sources alone (the Upper Passaic River, the tributaries, the CSO/SWOs, and Newark Bay) cannot explain the measured 2,3,7,8-TCDD concentration in the river. Note that the 2,3,7,8-TCDD concentrations from the upland external sources (the Upper Passaic River, the tributaries, the CSO/SWOs) are approximately two orders of magnitude less than the measured concentration in the recently-deposited (Be-7-bearing) surface sediments. Northern Newark Bay is approximately one order of magnitude lower, likely due to the impacts of the Lower Passaic River on this water body. Consequently, another source of 2,3,7,8-TCDD is necessary to achieve a closed contaminant mass balance. The only other source that could explain the target concentrations in the Lower Passaic River is the resuspension of legacy sediments. The mass balance calculated for 2,3,7,8-TCDD, shown on Figure 4-3a bottom panel and Figure 4-3b, indicates that resuspension accounts for about 87 to 100 percent, with a best estimate of 97 percent of the 2,3,7,8-TCDD observed in recently-deposited sediments in the Lower Passaic River.

Similar results were observed for Total TCDD (Figure 4-4a,b); however, for Total TCDD, the relative difference between the measured concentration in the Lower Passaic River and the concentrations in the external sources is less than the corresponding difference observed for 2,3,7,8-TCDD. The Total TCDD concentration difference among the upland external sources is only about one order of magnitude, as opposed to two

[9] "Target concentration" represents the average contaminant concentration in recently-deposited (Be-7-bearing) sediments in the Lower Passaic River between RM2 and RM12.

orders of magnitude for 2,3,7,8-TCDD. Even though the variation is much less, sediment resuspension is still necessary to achieve a closed contaminant mass balance. While all external sources account for about 1 to 28 percent with a best estimate of 8 percent of the Total TCDD mass balance, sediment resuspension accounts for 76 to 97 percent with a best estimate of ~ 92 percent of the contaminant mass.

The Newark Bay contribution to the Lower Passaic River dioxin contaminant burden ranges from less than 1 percent to 13 percent for 2,3,7,8-TCDD, with a best estimate of 3 percent. For Total TCDD, Newark Bay contribution ranges from less than 1 percent to 21 percent, with a best estimate of 5 percent. The concentrations of these contaminants in the river surface sediments are greater than the reported concentrations in the bay. These results indicate that the Lower Passaic River is a source of contamination to the bay.

Total PCB Mass Balance

The fate and transport of Total PCBs is influenced by sediment resuspension (Figure 4-5a, b). The Total PCB concentration in Newark Bay is about two times lower than the Lower Passaic River concentration and the Upper Passaic River concentration is about three times lower than the Lower Passaic River concentration. These concentration patterns in the source signatures indicate a dominant resuspension contribution of Total PCBs to the Lower Passaic River with a best estimate of about 81 percent and a range of 59 to 90 percent. Upper Passaic River is the most important external source of total PCB contamination to the Lower Passaic, with a best estimate of 11 percent (range of 4 to 22 percent of the overall mass), while the Newark Bay contributes about 7 percent (range of less than 1 to 25 percent) of the overall mass.

PAH Mass Balance

In the model, benzo[a]pyrene (Figure 4-6a, b) and fluoranthene (Figure 4-7a, b) represent the PAH contaminant compounds directly optimized by the model. For both of these compounds, the average PAH concentration in the Upper Passaic River is higher (approximately 1.5 times) than the Lower Passaic River average PAH concentration. The tributaries, the CSOs/SWOs and the 1995 surface sediment concentrations are comparable to the measured PAH concentration in the 2005-2007 Be-7-bearing sediments in the Lower Passaic River. The Newark Bay average PAH concentration is about two times smaller than the Lower Passaic River concentration. Because the average PAH concentration in the Upper Passaic River is higher than the target concentration (Lower Passaic River) and the other sources have similar PAH concentration, the contribution of the Upper Passaic PAH to the Lower Passaic PAH contamination is larger than any other compounds used in the mass balance. The Upper Passaic River contribution ranges from 27 to 70 percent for benzo[a]pyrene, with a best estimate of 53 percent and for fluoranthene from 24 to 64 percent with a best estimate of 47 percent. Resuspension of the historical inventory accounts for about 39 percent (range of 17 to 58 percent) of the PAH contaminant burden of the Lower Passaic River. Newark Bay's PAH contribution range from less than 1 percent to 30 percent, with a best estimate of approximately 6 percent.

Although higher PAH concentrations were observed in the tributaries and CSOs, comparable to observations in the Upper Passaic River, the relatively small solids contributions from the tributaries and CSOs limits their combined contribution to less than 17 percent.

Pesticides Mass Balance

The average 4,4'-DDE concentration in the Upper Passaic River is roughly four times lower than the measured concentration in the Lower Passaic River (Figure 4-8a, b). The 4,4'-DDE concentration in Newark Bay is slightly lower than the concentration in the Lower Passaic River. The average 4,4'-DDE concentration of the 1995 surface sediment source is only slightly higher than the 2005-2007 Be-7-bearing sediments in the Lower Passaic River (approximately 30 percent higher). While the Second and Third River 4,4'-DDE concentration overlaps with measured 4,4'-DDE in the 2005-2007 Be-7-bearing sediments in the Lower Passaic River, the limited solids load from these tributaries cannot account for the 4,4'-DDE mass in the river. The resuspension of the historical inventory contributes between 52 to 88 percent of the 4,4'-DDE mass in the Lower Passaic River, with a best estimate of 78 percent. Newark Bay contributes about 8 percent of 4,4'-DDE mass (range of less than 1 to 34 percent) and the Upper Passaic River contributes about 10 percent (range of 4 to 21 percent). The combined contribution from tributaries SWOs and CSOs range from 1 to 10 percent, with a best estimate of about 4 percent.

The gamma-Chlordane concentrations in the tributaries are about two to four times higher than that of the measured gamma-Chlordane in the 2005-2007 Be-7-bearing sediments in the Lower Passaic River (Figure 4-9a, b). Notably, both the Upper Passaic and the 1995 0-6 inch surface sediment have a lower gamma-Chlordane concentration compared to the measured gamma-Chlordane in the 2005-2007 Be-7-bearing sediments in the Lower Passaic (about 30 percent lower). Since the average gamma-Chlordane concentrations in the tributaries, SWOs and CSOs are higher, the combined contribution to the Lower Passaic River from these sources ranges from 4 to 25 percent, with a best estimate of 13 percent. While this fraction is relatively small, it is the amount needed to raise the gamma-Chlordane concentration in Be-7-bearing sediments above the concentrations observed in sediments from the Upper Passaic River and Newark Bay, as well as in resuspended sediments. The Upper Passaic contributes about 32 percent of the gamma-Chlordane contamination to the Lower Passaic. The resuspension of the historical sediment inventory accounts for about 32 to 70 percent of the gamma-Chlordane contamination in the Lower Passaic River, with a best estimate of 52 percent. Newark Bay contribution ranges from less than 1 to 19 percent of the gamma-Chlordane contamination to the Lower Passaic River, with a best estimate of approximately 3 percent. The gamma-Chlordane contributions from the Upper Passaic River, Newark Bay and resuspension remain significant because of the relatively large mass of solids contributed by these sources.

Metals Mass Balance

Similar to 4,4'-DDE, the fate and transport of copper, chromium, mercury, and lead in the Lower Passaic River is dominated by sediment resuspension. In the case of copper (Figure 4-10a top panel), higher concentrations relative to the target concentration were observed in the Second River/SWOs and the CSOs, as well as the resuspension source.

Copper concentrations in the other sources were less than the average target concentration. Given that the solids contribution from the Second River and CSOs are insignificant relative to the resuspension contribution, a mass balance for copper would need a significant resuspension contribution to explain the high target concentration. This is confirmed by the model-estimated copper budget (Figure 4-10a bottom panel and Figure 4-10b), which shows that resuspension accounts for 72 percent of the contaminant burden (range of 45 to 85 percent), while Newark Bay, the Upper Passaic and CSOs account for 12 percent (range of less than 1 to 40 percent), 14 percent (range of 5 to 25 percent) and 1 percent (range of less than 1 to 6 percent), respectively.

The relative concentrations of chromium (Figure 4-11a top panel) and mercury (Figure 4-12a top panel) in the various sources show higher or comparable average concentrations in Newark Bay and resuspension sources and lower concentrations for other sources, relative to the target concentrations. A mass balance for these metals can only be obtained by a large resuspension contribution to explain the target concentrations. This observation is confirmed by the best estimate and Monte Carlo mass balance results for chromium (Figure 4-11a bottom panel) and mercury (Figure 4-12a bottom panel). Resuspension of sediment accounts for approximately 74 percent of chromium and approximately 75 percent of mercury, both with a range between 44 and 88 percent. Both chromium and mercury also have similar contributions from Newark Bay and the Upper Passaic River, with respective values of 15 and 10 percent for chromium and 14 and 11 percent for mercury.

Average concentrations of lead from the various sources are shown in the top panel of Figure 4-13a. Lead concentrations are higher in the Second River/SWOs, CSOs and the resuspension source, relative to the average target concentration in the Lower Passaic River. Because the solids contribution from the Second River/SWO and CSOs are relatively small, a significant resuspension input is needed to explain the observed target concentration. The mass balance calculated for lead (Figure 4-13b, bottom panel) indicates a best estimate of 71 percent resuspension contribution to the overall lead burden in recently-deposited (Be-7-bearing) sediments, with an uncertainty range of 48 to

83 percent. The best estimates of the lead contributions from Newark Bay and the Upper Passaic River are about 7 and 19 percent, respectively, while the tributaries, SWO and CSOs contribute a combined 3 percent.

Iron and TOC Balance

Average source concentrations for iron indicate higher iron concentrations and, by association, higher fractions of fine particles in Newark Bay and the Lower Passaic River sediments relative to the other sources (Figure 4-14a top panel). The resulting mass balance (Figure 4-14a bottom panel) indicates between 29 to 72 percent, with a best estimate of 54 percent of the iron in Be-7-bearing sediments originating from resuspension. The iron contribution from Newark Bay ranges from less than 1 to 52 percent, with a best estimate of approximately 18 percent. The Upper Passaic River contributes a best estimate of 24 percent (range of 9 to 43 percent) of the iron burden to the target area.

Unlike iron, which indicates an appreciable Newark bay contribution, TOC in Newark Bay is low relative to other sources (Figure 4-15a, top panel). The TOC mass balance indicates a best estimate resuspension contribution of 72 percent to the TOC burden in the Lower Passaic River, with a range of 48 to 83 percent (Figure 4-15a bottom panel).

4.2.2 Inferred Fate and Transport Model for contaminants

Two contaminant mass balances could not be fully quantified in the EMB model due to data gaps/limitations and the degree of particle affinity of any given contaminant. For example, dieldrin was generally not detected in the Phase 1 Newark Bay dataset, thus only the Phase 2 data with some detected values were used and an inferred best estimate mass balance was developed for dieldrin.

Furthermore, because Low Molecular Weight (LMW) PAHs may be affected by dissolved phase concentrations as well as other contaminant degradation processes, they were not explicitly included in the EMB model. However, the best estimate EMB model solids balance was used to calculate a mass balance for phenanthrene, used as a surrogate for LMW PAH compounds. A summary of the inferred best estimate mass balances is as follows:

- The inferred best estimate mass balance (Figure 4-16) for dieldrin compares with that estimated for 4,4,'-DDE, with resuspension, Newark Bay, and the Upper Passaic River accounting for 73 percent, 7 percent, and 12 percent of the target burden, respectively.
- Phenanthrene was characterized at each source (the Upper Passaic River, tributaries, CSOs/SWOs, Newark Bay, and resuspension) and was used as a surrogate to represent LMW PAH. Unlike the other PAH compounds, benzo[a]pyrene (Figure 4-6) and fluoranthene (Figure 4-7), which indicate slightly higher contributions from Upper Passaic River relative to resuspension, the phenanthrene mass balance (Figure 4-17) indicates about a 47 percent and 42 percent resuspension and Upper Passaic River contributions, respectively. Newark Bay contributes about 2 percent of the phenanthrene in the Lower Passaic River, comparable to Saddle River with 4 percent.

4.3 Evaluation of EMB Model Performance

Model-calculated receptor concentrations for all parameters were evaluated through a statistical indicator referred to as the NME, which was defined in Section 3.7. Note that the NME expresses the bias in model predictions and observations, and gives an indication of overestimation (NME >0) or underestimation (NME <0) for each parameter.

Estimates of the NME indicate that the best estimate EMB model optimization resulted in predicted recently-deposited concentrations in the Lower Passaic River for the 13 parameters within 25 percent of the observed values, with the exception of gamma-Chlordane, which is under-predicted by 38 percent (see red columns in Figure 4-18).

Evaluation of model performance for the remaining nine parameters (see blue columns in Figure 4-18) also shows very good fits, with an NME within 25 percent for most parameters, with the exception of indeno(1,2,3- cd)pyrene, which is under-predicted by 28 percent.

4.4 Sensitivity Analysis

Uncertainties in source and receptor compositions and spatial variability in parameter concentrations were incorporated into the model solution through the Monte Carlo analysis described above. This section presents the result of additional analysis performed to assess the impact of compromised SWO contaminant concentrations (Table 4-3) and the model solids constraint (Table 4-4). The sensitivity results are discussed below.

Impact of Stormwater Data

The impact of compromised SWO data was evaluated by performing a model simulation using separate source compositions for Second River and the SWOs (the SWO contribution was separated from the Second River, with the SWO contaminant profile represented by the average of the compromised SWO data). The results of this scenario were not significantly different relative to the best estimate scenario (Tables 4-2 and 4-3, respectively). As expected, the use of the SWO data as an individual source did not affect the model calculations, most likely, because the SWOs, like the other tributaries, are minor solids contributors.

Impact of Model Solids Constraint

The best estimate solution, which was simulated using a solids constraint which required that the total solids fraction should be one, was redone without this constraint. There were slight differences between the best estimate solution (Table 4-2) and the relaxed solids constraint scenario (Table 4-4). In general, the differences were within the uncertainty estimated by the best estimate scenario of the Monte Carlo analysis. When the solids constraint was relaxed, the model predicted the solids fractions with an error of 8 percent, a value within the variability inherent in the contaminant measurements. The agreement between these two scenarios suggests that the contaminants profiles provide adequate constraint on the mass balance, as well as a strong mathematical basis to track the sediment types that are mostly associated with the contamination.

4.5 Assessment of the Cooperating Parties Group (CPG) 2008-2009 Data

In this mass balance model, the receptor concentration was defined by the contaminant concentration measured in Be7-bearing surface sediment samples collected during the USEPA 2005 and 2007 sampling events (representing the top 1 inch of sediment). The sources of fine-grained solids to the river were the Upper Passaic River, tributaries, CSOs and SWOs (sampled in the 2007-2008 sampling events), and Newark Bay (sampled as part of the Phase I and II field investigation of Newark Bay, TSI 2007, 2008). The source characteristics for resuspension of Lower Passaic River sediments were represented by the surface sediment (0-6 inch) concentrations from the 1995 TSI dataset.

In 2008, the CPG collected low resolution cores; however, the samples did not characterize recently-deposited sediments (*i.e.,* Be-7-bearing). In the main stem of the Passaic River, surface sediment concentrations between the 1995 TSI and the 2008 CPG were compared in Data Evaluation Report No. 4 in Appendix A, and the results indicate that median surface sediment contaminant concentrations have not changed much through this period.

For completeness of the EMB model, the 0 to 6-inch surface sediment concentrations reported by the CPG for the tributaries and Upper Passaic River were compared to the data used in the models. In the mass balance, each source term was defined by a Monte Carlo simulation to generate a bounded-normal distribution of possible contaminant concentrations. Table 4-5 provides a comparison of contaminant concentrations reported for the CPG 2008 surface sediments along with the Monte Carlo simulation range that was used to characterize each source term in the mass balance. For comparison purposes, the actual USEPA samples that were used in the Monte Carlo simulation are also provided. For all four external sources (Saddle River, Second River, Third River, and Upper Passaic River), the CPG 2008 surface sediment data generates average contaminant concentrations that fall outside the Monte Carlo simulation range. The CPG 2008 Dundee Dam data (Upper Passaic River) were generally higher than the Monte Carlo simulation range, while the CPG 2008 tributary data were lower than the range. As discussed above (and presented in Table 4-5), this difference is likely associated with sampling depths that represent different physical/contaminant regimes. Above Dundee Dam, 0 to 6 inches of silty sediment is likely characterizing deeper legacy sediments, so higher sediment concentrations are expected; whereas on the sandy tributaries, a 0 to 6-inch sample is likely capturing the underlying sand, which reduces the overall sample concentration. For the two tributaries with higher 2,3,7,8-TCDD concentrations than used in the model analysis, these stations are likely to be impacted by tidal transport of Lower Passaic River sediments into the tributaries during low flow periods. Consequently, the existing contaminant mass balance does not need any modification since the CPG 2008 sampling event was not designed to characterize the source term or solids transported from these sources to the river, and in some cases may be impacted by solids from the Lower Passaic River itself.

5 FORECASTING CONTAMINANT CONCENTRATIONS

The goal of this chapter is to integrate several of the analyses and observations described in the previous chapters to develop a basis to forecast future contaminant concentrations in surface sediments. The forecasting formulation represents the river section between RM2 and RM12 as a single system consisting of 1) a water column where mixing of particles from external sources and resuspension occurs; and 2) a mixed-layer surface sediment bed to which particle deposition from the water column occurs. The rationale for using this representation of the river section from RM2 to RM12 is based on observations of recently-deposited sediments which show little longitudinal variation in median concentrations (see Data Evaluation Report No. 4 in Appendix A). There are concentration gradients in the recently-deposited sediments at either end of this river section which represent the mixing zones with Upper Passaic River (from RM12 to RM17) and Newark Bay (from RM0 to RM2). Note however that this observation related to recently-deposited sediments does not suggest that surface sediments show little variability. As shown in Data Evaluation Report No. 4 in Appendix A, surface sediment concentrations of the various contaminants vary by several orders of magnitude. The variability in surface sediment concentration (as well as other sources of variability) was accounted for stochastically by a Monte Carlo simulation approach for the forecasting analysis, providing an estimate of future contaminant concentrations in the river bed.

The forecasting analysis integrated the relative solids and contaminant contribution results from the EMB model, the observed surface sediment concentrations, current contaminant compositions of external sources, and historical trends of sediment contamination from dated sediment cores, as discussed below. Similar to the EMB model analysis, a Monte Carlo analysis consisting of 10,000 iterations was performed to quantify uncertainties in contaminant forecasts for the single system. These forecasts can be used to estimate the future contaminant concentrations in the 0-6 -inch surface sediment layer, the interval which corresponds to the bioactive sediment layer. The ability to predict future exposure point concentrations in this horizon is important for risk assessments and to evaluate the FFS remedial alternatives.

This chapter is divided into two major sections: "Development of Concentration Half Times[10] for the Excess Passaic River Sediment Burden" and "Forecasts of Sediment Concentrations for FFS Remedial Alternatives." The first section describes the results of an analysis which uses the dated sediment cores to examine the decline in contaminant concentrations over time. As part of this analysis, baseline contaminant levels in the external upland sources are subtracted from the Lower Passaic River sediment concentrations observed in the dated cores, yielding the component of the annual contaminant burden that is due to loads "internal" to the Lower Passaic River. This is also referred to as the "excess sediment burden." Nearly all internal contaminant loads present in the Lower Passaic River can be attributed to legacy sediment resuspension. It is essential to quantify the internal burden since it represents the contamination that would be controlled by a remedial action performed on the Lower Passaic River. Using the observed decline of this burden over time, the rate of concentration decrease can be described by a first-order exponential decay curve with an estimated half time based on the rate of the natural recovery process (*i.e.,* the time it takes for the concentrations in depositing sediment to decline by half as a result of these processes). Once the half times for the different contaminants were determined, regression analysis was used to compare the contaminant-specific half times and determine a single half time for the excess sediment burden in the Lower Passaic River.

In the second section, the half times developed from the dated sediment core chronologies for the internal resuspension load were used, together with the results of the EMB model, to forecast future concentrations in the bioactive sediment layer. The forecast calculations were made for the best estimate scenario using average contaminant concentrations and other model inputs, and uncertainties were quantified by Monte Carlo analysis. These forecasts are made for the FFS Remedial Alternatives, including: No

[10] The use of the term "half time" in this sense is not to imply decay or destruction of 2,3,7,8-TCDD over time, akin to the decay of a radionuclide. Rather, the term here is used to express a rate for the decline of 2,3,7,8-TCDD concentrations in the solids accumulating at each coring location. Specifically, the half time is the time required for the 2,3,7,8-TCDD concentration to decline to half of its current value. The processes that affect the decline are multifold, including many of the fluxes and processes that occur in an urban estuary. The "half time" expression is just a means to encompass these processes and note their net effect on concentration through time.

Action (Alternative 1), Deep Dredging with Backfill (Alternative 2), Capping with Dredging for Flooding and Navigation (Alternative 3), and Focused Capping with Dredging for Flooding (Alternative 4). Detailed description of these alternatives is provided in Chapter 4 of the FFS Report.

5.1 Development of Concentration Half Times for the Excess Passaic River Sediment Burden

The dated sediment core profiles for the Lower Passaic River and the Upper Passaic River at Dundee Dam describe the chronologies of contaminant concentrations in the sediment. By careful selection of the coring locations and radionuclide dating of the sediment layers, the time-dependence of contaminant concentrations can be discerned. As discussed in Data Evaluation Report No. 3 in Appendix A these sediment records are a proxy for contaminant concentrations on suspended matter in the water column at the time of deposition. Because tidal mixing integrates suspended matter and the associated contaminant loads over distances of several miles, each dated sediment core records the relative intensity of loads as they are deposited on the river bottom in its vicinity.

To the extent that the core records yield regular variations over time (*e.g.,* a steady decline in contaminant concentrations from depth to the surface), the trends in the core chronologies can be extrapolated and used as a basis to estimate future conditions in the absence of remediation. Essentially, the rate of contaminant concentration decline documented by the core implies a rate of recovery for the river's sediments in the absence of any marked changes in loads or processes. In most instances, these loads and processes (*e.g.,* the integration of a large watershed area) are difficult to change or redirect without major intervention.

The dated sediment cores document the impacts of internal and external loads to annual deposition, the equivalent of the annual Be-7-bearing sediment deposits. In order to forecast future impacts of legacy sediment-related loads, it is first necessary to distinguish the component of the water column-based sediment record (*i.e.*, the dated sediment cores) that is due to legacy sediment resuspension from that which is due to external loads.

The EMB model, presented in Chapters 3 and 4, used available field data to represent the contaminant sources associated with sediment flux from each of the major tributaries, the CSOs/SWOs, Newark Bay, and the Upper Passaic River. The EMB model also used the 1995 surface sediment data to estimate the conditions of the internal contaminant source: the resuspension of legacy sediments. After balancing the loads from all the sources with the known conditions of recently-deposited (Be-7-bearing) sediment, the EMB model produced a set of fractions describing the solids contribution from each of the sources. These fractions can be used to separate the loads measured in the dated sediment cores into the contributions from each source, which is necessary to identify which portion of the contaminant load will be controlled by remediation. The underlying premise of this approach is that the relative solids contributions from each of the solids sources to annual deposition as recorded in the cores has remained constant over for the historical period examined. This is for the period 1980 to 2005 as described below.

5.1.1 Natural Recovery Processes Occurring in the Lower Passaic River

Natural recovery processes are likely occurring in the Lower Passaic River and impacting some contaminant concentrations over time. These trends are observed in the dated sediment core profiles presented in Data Evaluation Report No. 3 in Appendix A, with concentrations declining from the 1980s to 2005 for some contaminants. Table 5-1 summarizes the average 1980s concentrations for some of the contaminants and compares these values to the average 2005 surface sediment concentrations.

The observed concentration decline may be due to multiple factors, including: natural recovery processes (such as mixing and burial) and the elimination of direct discharges, the combination of which curtailed the contaminant load over time. For this analysis, only sediment samples dated from 1980 and later were included. Based on the dated cores, this period was inferred to represent natural recovery-type reductions in concentration more than reductions caused by the elimination of direct contaminant discharges. These natural reductions are assumed to continue into the future.

5.1.2 Data Available for Estimating the Half Times and Developing the Trajectories

Each of the sources and the data available to quantify the decline in concentrations over the last three decades are described herein:

- **Lower Passaic River** – There are five high resolution sediment cores collected in 2005 that document the characteristics of fine-grained suspended solids over time, representing 12 miles of the Lower Passaic River and providing a basis for an analysis of sediment contaminant concentrations as they change through time (see Data Evaluation Report No. 3 in Appendix A).
- **Upper Passaic River** – One of the high resolution cores taken from Dundee Lake in 2005 by scientists from Rensselaer Polytechnic Institute (RPI) contains sufficient data to describe the trend in contaminant concentrations in the Upper Passaic River over the last 30 years. This core is presented in Figures 3-1, 3-2, 3-5 and 3-6 in Data Evaluation Report No. 2 in Appendix A. With the exception of PAHs and dieldrin, the detected contaminants have had relatively constant concentrations in the suspended sediments above Dundee Dam since about 1990. Previous to that time, there were elevated contaminant concentrations in the core segments and, by inference, in the contemporaneous suspended solids transported over the dam. PAHs and dieldrin appeared to decline in concentration until about 1990, when the trend reversed and concentrations began to increase again. In addition, data from several core tops, surface sediment samples, and sediment traps collected in 2007-2008 were used to estimate the current average concentration on suspended sediment (Be-7 bearing).
- **Newark Bay** – No known high resolution cores exist to quantify depositional/contaminant chronologies in the Newark Bay sediments for the post-1990 period. The surface sediment samples from 2005 indicate a spatial gradient for many of the contaminants from south to north, but there is no information on temporal change in sediment concentrations. The EMB model used the five northern

samples (see Table 3-4) to define the Newark Bay end member for use in the model. The trajectory calculations also used these northern samples to calculate the Newark Bay component.

- **Tributaries** – There are no temporal data available to determine the changes of sediment contaminant concentrations over time in the Saddle River, Second River or Third River.
- **CSO/SWOs** – There are no temporal data available to determine the changes of contaminant concentrations over time in the releases from either the CSOs or the SWOs.

To determine the temporal changes in the internal (resuspension) Lower Passaic River contribution to the total contaminant load, each of the external sources was quantified and subtracted from the total concentration, using the solids fractions obtained from the EMB model results.

In the absence of information to the contrary, the tributaries and the CSO/SWO components were assumed to have constant contaminant concentrations from the 1980s to the end of the trajectory forecast. Since the EMB model found that the combined sediment contributions from these sources were less than 5 percent of the entire sediment load in the river, their contribution is small enough to warrant an assumption of this nature without materially affecting the outcome of the trajectory forecasts.

The Upper Passaic River contribution was defined by a linear interpolation of concentration versus time between each core segment from the RPI core (see Data Evaluation Report No. 3 in Appendix A). After the last data point on that core (2005) and through the end of the trajectory forecasts, the Upper Passaic component was assumed to be constant. The constant concentration was an average of the core tops from two RPI cores (one previously mentioned) and two Malcolm Pirnie cores collected early in 2007, as well as a number of surface sediment and sediment trap samples from the 2007/2008 sampling program.

The remaining two components are the Lower Passaic River resuspension component and the Newark Bay component. Given the close link between these two water bodies and the lack of a Newark Bay core to separately track fine-grained suspended matter from the Bay, there is no way to separate their rates of decline. As a result, both contributions are assumed to decline at the same rate. Therefore, when calculating the rate of decline, the portion of the total contaminant load remaining after subtraction of the Upper Passaic River, tributary, and CSO/SWO loads is defined as the "excess load".

The assumption that Newark Bay concentrations are declining at a similar rate to the Lower Passaic River sediments is rational, and perhaps conservative, given that the northern end of Newark Bay is the end member used in the EMB model. Data Evaluation No. 2 in Appendix A discusses the evidence to support the premise that 70 percent of the dioxin load in Newark Bay is derived from the Lower Passaic River. Since so much of the sediment dioxin load in Newark Bay originates from the river, it is appropriate to assume that the rates of concentration decline are similar. For other contaminants, the Lower Passaic River's contribution to Newark Bay is probably much less due to other sources. However, in these instances, the Newark Bay concentrations at the southern end of the Bay are used as the "base" for the Newark Bay contribution (*i.e.,* northern Newark Bay concentrations are not permitted to decline below this concentration). Thus for those contaminants with a strong north-to-south gradient in Newark Bay (suggesting an important Lower Passaic River contribution), the large difference between the ends of the bay is allowed to decline at the rate observed for the Lower Passaic River. For those contaminants with a shallow or no gradient, the concentration on Newark Bay solids delivered to the Lower Passaic River remains essentially constant over time.

5.1.3 Calculating the Half Times

Figures 5-1 through 5-10 show the excess concentration, obtained by subtracting the products of each upland source's concentration (based on averages of available data) and solids fraction (from the EMB model) from the concentrations assigned to each slice of the five high-resolution cores from the Lower Passaic River. The resulting datasets were fitted to a first-order exponential decay curve as described above. While the exact mechanism(s) and rate of decline for this excess concentration are not specifically known, the results clearly indicate a decline for most contaminants. The choice of a first order decay process is consistent with the expected processes affecting most contaminants in this system, specifically dispersion, bioturbation, diffusion, and degradation. For each of these processes, the rate at which they occur is linearly dependent on the contaminant concentrations (*e.g.,* the higher the concentration, the higher their rates of dispersion, diffusion, and degradation). The basic first-order decay equation is presented as Equation 5-1 below.

$$C_t = C_o e^{-\lambda t}$$ Equation 5-1

Where

C_t:	excess sediment concentration at a given time
C_o:	excess sediment concentration at the initial time
λ:	exponential decay parameter
t:	time

Moreover, the exponential decay parameter (λ) is related to the half time (Equation 5-2), or the estimated time for the contaminant concentration to decrease by half:

$$t_{half} = \frac{\ln(2)}{\lambda}$$ Equation 5-2

Where

t_{half}:	time estimated for the 1980 concentration to decline by half

The regression fits of the exponential regression lines, coefficient of determination of the fits (R^2), confidence interval of the half times, and the level of significance of the regression are included in Figures 5-1 through 5-10. The fits of the exponential regression lines were shown to be statistically significant ($P<0.05$) for all of the parameters except gamma-Chlordane and the sum of High Molecular Weight (HMW) PAHs. For these two contaminants, the confidence intervals, especially the upper interval, cannot be estimated. Further, one contaminant, dieldrin, was shown to have an increasing, statistically significant trend. An increasing trend cannot be explained by the geochemical constructs inherent in this analysis, so dieldrin was not forecast.

Forecasting the future behavior of LMW PAHs was not performed due to the inability of the EMB model to balance the contribution of the various sources to the Lower Passaic River for these contaminants, which may indicate that their fate and transport is not strictly tied to fine-grained sediments. However, the measured trend of LMW PAH concentrations from the dated sediment cores, which is declining with a half time of about 63 years (Figure 5-10) provides an indication of sediment recovery for LMW PAHs.

The individual contaminant-specific half times and associated confidence intervals for all contaminants are listed in Table 5-2. Note that these are not true half times for the contamination in the Lower Passaic River; rather, they are half times for the portion of the contamination that is attributable to resuspension in the Lower Passaic River and input from Newark Bay ("excess concentration"). This is the only portion that is assumed to be declining exponentially. Comparison of the confidence intervals of 2,3,7,8-TCDD, total PCB, 4,4'-DDE, mercury, lead, copper, and gamma-Chlordane shows significant overlap suggesting a common exponential decline for the excess sediment burden in the Lower Passaic River. To estimate this common half time for the excess sediment burden, a first-order regression model was developed incorporating the excess contaminant concentrations for multiple contaminants and their estimated time of deposition in the Lower Passaic River. Details of this regression analysis are described in Attachment B. The results of the analysis indicate a common average half time of approximately 35 years for the excess sediment burden. The 95 percent confidence interval for this common half time is from 27 to 48 years. Although only seven contaminants were included in the model, this result also applies to other particle-reactive contaminants in the Lower Passaic River that have a significant resuspension source term.

5.2 Forecasts of Sediment Concentrations for FFS Remedial Alternatives

This section describes the process to determine the best-estimate, post-remediation contaminant concentrations and associated uncertainties in surface sediments for the following four alternatives:

- No Action (Alternative 1)
- Deep Dredging with Backfill (Alternative 2)
- Capping with Dredging for Flooding and Navigation (Alternative 3)
- Focused Capping with Dredging for Flooding (Alternative 4)

For each alternative listed, post-remediation surface sediment concentrations were forecast for the contaminants listed in Table 5-1. All of the remedial alternatives listed above include the 200,000 cubic yards of sediment removed behind a coffer dam under the Tierra Removal Phases 1 and 2 (see FFS Report Section 4.0 for more information). However, this removal action was not explicitly included in the empirical trajectory forecast for the following reasons:

- Surface sediment concentrations for 2,3,7,8-TCDD in the Tierra Removal Phase 1 and 2 areas compare to the range of values reported for other locations within the FFS Study Area. This observation also applies to other contaminants. Thus inclusion of these values does not affect the mean concentration estimates or the associated statistics used in the model.
- Because the removal occurred within confinement, release of extremely high concentration in the deeper sediment layers in Tierra Removal Phase 1 and 2 areas is not anticipated.
- The forecast trajectory model represented the surface sediments in the FFS Study as a single system represented by the average. Excluding the post-dredging anticipated concentrations of approximately zero in the spatially small Tierra Removal Phase 1 and 2 areas does not affect the average sediment concentrations used to represent the legacy sediments in the model or the variability in concentrations represented in the Monte Carlo simulation.

5.2.1 Overview of Remedial Alternatives

Alternative 1 - No Action – Although the No Action Alternative involves no active remedial technologies, natural recovery processes (*e.g.*, mixing and burial) may be at work to reduce contaminant concentrations in sediments over a period of interest.

Alternative 2 – Deep Dredging with Backfill – This active remedial alternative specifies removal of the fine-grained sediments present in the FFS Study Area, bank to bank, by dredging. The intent of Alternative 2 is to remove as much contaminated fine sediment as practicable between RM0 and RM8.3. Dredging outside the Tierra Removal Phase 1 and 2 areas would begin in March 2018 and all activities will be completed in October 2028, and backfill placement will be completed in July 2029. The release of sediments and contaminants during the dredging process is not represented in the empirical forecast model.

Alternative 3 – Capping with Dredging for Flooding and Navigation – This active remedial alternative specifies a combination of dredging and capping, bank to bank, of the fine-grained sediments present in the FFS Study Area. The intent of Alternative 3 is to sequester the contaminated sediments under an engineered cap, while dredging enough material to limit flooding that might be caused by the installation of a cap and to accommodate current and projected future use of the federal navigation channel from RM0.0 to RM2.2. Dredging outside the Tierra Removal Phase 1 and 2 areas would begin in March 2018 and will be completed in November 2022. Backfill and cap placement activities will be completed in December 2022. The release of sediments and contaminants during the dredging processes is not represented in the empirical forecast model.

Alternative 4 – Focused Capping with Dredging for Flooding – This active remedial alternative specifies a combination of dredging and capping of discrete areas of fine-grained sediments that add up to about one-third of the river bottom in the FFS Study Area. Dredging outside the Tierra Removal Phase 1 and 2 areas would begin in March 2018 and all activities will be completed in February 2020. Final cap placement is anticipated to be completed in March 2020. It was assumed that one-third of the area will be remediated. The release of sediments and contaminants during the dredging processes is not represented in the empirical forecast model.

5.2.2 Assumptions for the Active Remediation Alternatives

The methodology used to derive the trajectory forecasts are presented in detail in Attachment C. In order to forecast contaminant concentrations in surface sediments after active remediation (Alternatives 2 to 4), several assumptions were needed:

- From 1995 to the end of 2017, the concentration trends for the contaminants for all alternatives will continue to follow an exponential decline based on the half time values provided in Table 5-2 and estimated from contaminant histories obtained from the high-resolution cores. Beyond 2017, only the No Action alternative will continue this trend through the end of the trajectory analysis.
- For Alternatives 2, 3, and 4, a linear reduction in surface sediment concentration during the implementation of the remedy is assumed between the value in 2017 and the anticipated value at the end of the remedy. For Alternatives 2 and 3, surface sediment concentrations declined linearly from the value in 2017 to zero in 2029 and 2022, respectively. For Alternative 4, surface sediment concentrations declined linearly by one-third from the value in 2017 to 2020.
- After remediation is complete, the impact of any remedy on resuspension is proportional to the fraction of fine-grained sediment area addressed by the remedy. This premise is based on the observation that the majority of the contaminant burden is associated with fine-grained sediments. Thus the reduction in the resuspension contribution declines directly with the reduction in fine-grained sediment surface area. Therefore, for Alternatives 2 and 3, remediation of sediments from RM0 to RM8.3 results in a 75 percent reduction in the sediments and contaminants available for resuspension (*e.g.,* erosional silt areas) over the entire 17 miles of the Lower Passaic River. The exception to this is 2,3,7,8-TCDD. Because 2,3,7,8-TCDD is not found in the sediments above RM12 to an appreciable degree, the availability of 2,3,7,8-TCDD contaminated fine-grained sediment for resuspension is reduced by 88 percent (see the formula derivation in Attachment C).

- The average sedimentation rate (0.27 inches/year) remains unchanged by the remedy.
- Following remediation, surface sediment concentrations in unremediated areas will continue to decline exponentially with the same half time values provided in Table 5-2. This assumption does not account for any reductions in the flux of contaminants carried into the unremediated areas after the remediation of the lower eight miles. It also does not account for any remediation from RM8.3 to RM17.4 that might be planned by the Cooperating Parties Group (CPG). This assumption would tend to underestimate the benefits of remediating the lower eight miles.
- Initially, after remediation, the resuspension contribution from the capped or backfilled areas will be zero, due to the designed resistance to erosion or the use of sand as backfill. However, over time, it is anticipated that fine-grained sediments will settle on the cap, recreating the current sediment texture (*i.e.*, a fine-grained area that is capped with coarse sand will, over time, become covered with fine-grained sediments again). Thus, the volume resuspended from the remediated areas was allowed to linearly increase each year until a full 6-inch biologically active layer has been developed on top of the remediated area. Assuming 0.27 in/year of sedimentation this is calculated to take 22 years. After the 22-year period, resuspension from the remediated area will be at the same rate as for any other fine-grained area in the river.
- No decline in concentrations in the Upper Passaic River, the tributaries, or the CSO/SWOs will occur at any time in the future. Concentrations of Newark Bay suspended matter delivered to the Lower Passaic River will reduce exponentially (with the half times listed in Table 5-2) towards the level currently measured in the Be-7 bearing sediment at the southern end of the bay. Thus, the surface sediment concentrations in the Lower Passaic River will asymptotically approach the level of contamination represented by the combination of these external sources.

The final premise listed above refers to a “floor” or baseline value for each trajectory. Although the Newark Bay source is assumed to be dropping exponentially, it is not reasonable to assume that it will reach undetectable levels for most contaminants within the time period analyzed without remediation efforts. This analysis assumes that the interactions between Newark Bay and the Lower Passaic River continue as they are now, and that these interactions will not be impacted by changes to the system (*e.g.,* maintenance dredging). The samples from the northern part of the bay were used as the end members for the EMB model. For many contaminants, Newark Bay has an increasing contaminant concentration trend from south to north towards the mouth of the Passaic River. This indicates mixing of relatively cleaner southern Newark Bay sediments with comparatively more contaminated sediments from the Lower Passaic River. Thus, for the purposes of this analysis, the southern Newark Bay sediments were assumed to represent the lowest concentration that Newark Bay sediments can achieve without active remediation in the Bay.

Similarly, the concentration assigned to the resuspension component within the Lower Passaic River was also assigned a "floor" value. Because the resuspended sediment is comprised of sediments introduced from the sources as well as legacy contaminated sediments, it is natural to assume that the concentration of the resuspended sediment will not drop below the sum of the external source contaminant loads. The floor for the contaminant concentrations on resuspended sediments was calculated as the sum of the products of the constant sources (Upper Passaic River, tributaries, CSO/SWOs) and their solids fractions and the product of the Newark Bay "floor" value and the Newark Bay solids fraction.

This floor value was implemented into Equation 5-1 as follows:

$$C_t = (C_o - f)e^{-\lambda t} + f \qquad \text{Equation 5-3}$$

Where:

C_t:	sediment concentration at a given time
C_o:	sediment concentration at the initial time
f:	"floor" value calculated as described above.
λ:	exponential decay parameter derived in Section 5.1
t:	Time

In this way, the concentration of surface sediments approaches *f*, instead of 0 as given by Equation 5-1.

5.2.3 Calculation of the Best Estimate Trajectories

As described in the previous section, half times were calculated for each of the contaminants of concern listed in Table 5-1 by subtracting out the portions of the total concentration from the high resolution cores that were attributable to the Upper Passaic River, the tributaries, or the CSOs and SWOs. The exponential line fit through the data, then, represented the reduction in contaminant concentration due to natural recovery processes occuring in the Lower Passaic River and Newark Bay.

Using the average concentrations for each of the sources and the half time calculated from the high resolution cores, a natural recovery (no action) trajectory for annual deposition (equivalent to the Be-7-bearing sediment deposited in a given year) was fit through the concentrations for each source.

The EMB model was an optimization routine that systematically searched for the best set of solids contribution fractions that would balance the mass of each contaminant from each source. It was an over-constrained set of 13 equations with 7 unknowns. Because of modeling assumptions, simplifications to the system, and variations or errors in data sets, the optimization routine was not able to find a solution that perfectly balanced all 13 parameters. As explained in Chapter 4, the fit was good for most of the parameters. In the case of gamma-Chlordane, the fit was not as good, resulting in an error of 38 percent. Because of this lack of fit, the summation of the gamma-Chlordane contributions from each of the sources did not match the data collected in the main stem of the river between RM2 and RM12 during the 2007 sampling effort or the core tops from the 2005 high resolution cores. For most of the contaminants, model prediction yielded a sufficiently small NME that the contaminant trajectories passed through the concentration range represented by the 2005-2007 data. For gamma-Chlordane however, the trajectory fell significantly below the recent data points, and each source concentration was artificially increased by the percent error from the EMB model to bring the trajectory up to match the measured data.

As discussed above for the active remedial alternatives, treatment of the river bottom is expected to prevent resuspension of contaminated sediment. However, these treatments would also initially prevent resuspension of any sediment on the cap or backfill. Because the cap or backfill will be composed of clean sand and, in the case of a cap, may be armored in certain areas to prevent erosion due to high velocities, this assumption would apply for the early part of the remedy's design life. As time goes on, the river is expected to deposit silt particles on the top of the cap or backfill. These particles are then available for resuspension and mixing with other sources from the river. The amount of silt available for resuspension within the remediated area would increase from zero at the time of installation to a maximum level, at which point the resuspension from the remediated area would match the resuspension from unremediated areas.

In the calculation of these trajectories, it was assumed that the rate of resuspension from the remediated area would match that of unremediated areas once a 6-inch layer of sediment had been re-deposited on top of the capped or backfilled area. This layer would be biologically and physically active, and was assumed to be a vertically mixed surface layer. At a sedimentation rate of 0.27 inches per year on average, it would take 22 years for this layer to reach an average depth of 6 inches. For simplicity, the amount of resuspension on the cap or backfill was assumed to increase linearly from 0 to the level of the unremediated areas during this 22- year period. Since the remediation is assumed to be completed in 2029 (Alternative 2), 2022 (Alternative 3) and 2020 (Alternative 4), the newly re-deposited layer would be 6 inches thick by the years 2051, 2045 and 2042, respectively.

Since the calculations allow the remediated areas to eventually contribute to the resuspended sediment load in the river, it is necessary to estimate the concentration of the contaminants in this resuspended sediment. This material is derived from the upper 6 inches of the capped or backfilled surface. The contaminant concentrations in this layer initially would be zero, since the cap or backfill is assumed to be free of contaminants. This concentration would not be added to the river in the first year since the material would be designed to largely remain in place. As the remediated surface begins to accumulate sediments from the water column, it becomes more subject to resuspension. The concentration of contaminants in sediments resuspending from the remediated areas was calculated assuming that the upper 6 inches represents a mix of newly-deposited sediment and the cap or backfill material. Thus, in the second year, the upper 6 inches would equal on average 5.73 inches of clean cap or backfill material and 0.27 inches of deposited sediment. The contaminant concentration of this layer would be the volumetric average of the concentration on the newly deposited 0.27 inches of sediment and the 5.73 inches of clean material. Continuing this process, in the third year the contaminant concentration in the upper 6 inches would be a volumetric average of 5.73 inches of mixed cap or backfill material (from the previous year) with a concentration equal to that calculated the second year and 0.27 inches of newly-deposited material with a concentration equal to the forecast Be-7-bearing surface sediment concentration from the previous year. In each case, the two concentrations are mixed proportional to the thicknesses mentioned. This composite concentration was then applied to any resuspension occurring from the remediated areas for that year.

For the purposes of the risk analysis and for comparison of the remediation alternatives, it is most appropriate to compare the effects of the remediation on the upper 6 inches of sediment instead of simply the recently-deposited (Be-7-bearing) sediment. This is because the upper 6 inches represents what is typically considered the biologically active layer and thus represents the exposure point concentration for most biota. For the No Action alternative, the mean sediment concentration over the upper six inches of sediment can be estimated by averaging the annual sediment deposition for the previous 22 years as characterized by the dated sediment cores. When the upper 6-inch layer concentration for each of the contaminants is estimated in this way for the year 1995, all of the contaminant concentrations estimated from the dated sediment cores (except Total PCBs) fall within two standard errors of the mean value from the TSI 1995 surface sediment (0-6 in) dataset.

The 1995 TSI dataset does not report concentrations for all the PCB congeners, so the Total PCB concentration was estimated as the sum of the Aroclors. This differs from other samples in the 2005 and 2007/2008 sampling events, which report all of the congeners, and the Total PCB as a sum of congeners. These two sums are not always analogous. A regression analysis between Aroclor and congener-based total PCB estimates using 2005 to 2010 data indicated that Total PCBs by Aroclor was biased low by 25 percent (see Data Evaluation Report No 5 in Appendix A). Despite this difference, the Total PCB concentrations estimated by the EMB model agreed to within 2 percent of the measured data.

Assuming that the concentration trends observed for the past 25 years will continue into the future, surface sediment concentrations from 2005 to 2059 were forecast for the annual deposition (equivalent to the Be-7-bearing sediments deposited each year) for each contaminant following Equation 5-4. These concentrations were then used to estimate the exposure concentrations in the 0-6 inch biologically active layer of sediment using the process outlined in Attachment B. The placement of sand material to construct a sub-aqueous cap or to backfill after dredging is assumed to temporarily restrict fine-grained sediment resuspension, as described above. Given the many unknowns associated with remedial construction sequence for the various alternatives, no attempt has been made to predict short-term consequences during implementation, such as resuspension during dredging; these short-term impacts are incorporated into the mechanistic model (Appendix B) and addressed in the FFS. During the remediation, a linear reduction in surface sediment concentration is assumed between the value in 2017 and the anticipated value at the end of the remedy. After completion of each remedy, for the purposes of long-term forecasts, it has been assumed that all benefits of remediation are realized in the final year of the typical remedial alternative construction period (2029, 2022, or 2020 for Alternatives 2, 3, and 4, respectively). The following equation integrates the spatial extent of remediation and the processes affecting the 0 to 6 inch layer:

$$C_{REM} = \frac{f_{RSP}\left(C_{RSP}(1-b-d)+C_{cap}bc\right)}{1-b(1-c)f_{RSP}} + \frac{\sum C_i f_i}{1-b(1-c)f_{RSP}} \qquad \text{Equation 5-4}$$

Where:

C_{REM}: new recently-deposited (Be-7-bearing) sediment concentration following remediation in 2029, 2022, or 2020 for Alternatives 2, 3, and 4, respectively.

C_{RSP}: contaminant concentration for resuspending sediment (top six inch average)

C_{cap}: contaminant concentration on top of the cap or backfill (top six inch average)

C_i: contaminant concentration on incoming sediment from source, i

i: subscript representing all sediment sources other than resuspension

f_{RSP}: fraction of solids associated with resuspension

f_i: fraction of solids associated with source, i

b: fraction of fine-grained sediment area impacted by placement of cap or backfill material

c: ratio of resuspension occurring in remediated areas per unit area to that in unremediated areas

d: adjustment for fine-grained sediment area not impacted by remediation and not contaminated with dioxin (this value is zero for all contaminants other than dioxin.)

5.2.4 Calculation of the Trajectory Uncertainties

The best estimate trajectory calculations described above used the best estimates, or averages of all the concentrations and other inputs needed, for the trajectory forecast calculations. The uncertainties in best estimate trajectories were determined by Monte Carlo simulation for 2,3,7,8-TCDD, Total PCB, 4,4'-DDE, mercury, lead, copper, and gamma-Chlordane. Detailed description of the Monte Carlo analysis, which was composed of 10,000 iterations of randomly-generated input values to the trajectory calculation, is provided in Attachment A. The 10,000 Monte Carlo-generated inputs to the contaminant forecasts calculations include:

- Randomly generated contaminant inputs to the EMB model;
- Optimized EMB model solids balance output;

- Randomly-generated half times using the confidence bounds and a normal distribution assumption;
- Randomly-generated sedimentation rates developed using bootstrap analysis of the difference between the 1989 and 2007 bathymetric surfaces; and
- Randomly-generated estimates of the depth of the sediment mixed layer between 10 and 20 cm.

Uncertainties in the contaminant forecasts developed from the Monte Carlo analysis were based on the confidence interval (5^{th}, 25^{th}, 75^{th} and 95^{th} percentiles) of the 10,000 optimized solutions.

5.2.5 Best Estimate Trajectory for the No Action Alternative (Alternative 1)

Assuming that the concentration trends observed for the past 25 years will continue into the future, concentrations in the 0-6 inch surface sediment layer from 1995 to 2059 were forecast for each contaminant following the procedure outlined in Attachment B. This procedure assumes that the exponential decline noted in the combination of Lower Passaic River (internal resuspension) source and the Newark Bay source continues at the same rate noted for the last three decades. It also assumes that the "constant" sources (Upper Passaic River, tributaries, and CSO/SWOs) remain constant for the period of model simulation. The best estimate No Action Alternative concentration forecast is calculated using Equation 5-3 for Newark Bay and the resuspension term. All other sources are added in as constants. The best estimate No Action forecasts are presented in part A of Figures 5-11 through 5-17 (*e.g.*, Figure 5-11A) and Figure 5-18. Table 5-3 presents the percent reduction in forecast concentration in 2059 relative to 2017 level before the active remedies are to be implemented.

Part A of Figures 5-11 through 5-17 and Figure 5-18 also show the mean concentration reported in the 1995 TSI surface sediment dataset (red point). The error bars indicate two standard errors above and below the mean. The estimated concentration for the 0-6 inch biologically active zone is within this envelope in every case (see discussion on gamma-Chlordane adjustment above).

These results indicate that 2,3,7,8-TCDD surface sediment concentrations are forecast to decline by 59 percent (from 0.5 to 0.2 μg/kg) from 2017 to 2059 under No Action. For the other contaminants, the decline is 50 percent or less (Table 5-3a for percentages and Table 5-3b for the concentrations). The relatively larger decline in 2,3,7,8-TCDD compared to other contaminants is because the external sources (*e.g.*, Upper Passaic River, tributaries, CSOs/SWOs) are not significant contributors of 2,3,7,8-TCDD to the sediments of the Lower Passaic River. Contaminants like gamma-Chlordane and PAHs, which have seen no appreciable decline in the last 25 years, are not predicted to decline at all over the time period of the forecast. The smaller reductions seen for metals, DDE, and PCBs indicate that significant sources of these contaminants exist in the Upper Passaic River or Newark Bay. Although significant concentrations may exist in the tributaries or the CSO/SWOs, their small solids contribution prevents them contributing a large mass of hydrophobic contaminant to the Lower Passaic River.

5.2.6 Best Estimate Trajectory for Alternatives 2 to 4.

The other remediation alternatives involve dredging and capping/backfill described in Section 5.2.1. The forecast concentrations in the 0-6 inch layer are shown as orange lines for Alternative 2, green lines for Alternative 3, and purple lines for Alternative 4 on part A of Figures 5-11 through 5-17 and Figure 5-18. The percent reductions in forecast concentrations in 2059 relative to 2017 for each Alternative are tabulated in Table 5-3.

Overall, the trajectory results indicate that Alternative 4, the focused capping remedy, provides much less reduction in future concentrations compared to Alternatives 2 and 3. About a 90 percent reduction in 2,3,7,8-TCDD surface sediment concentrations was estimated by 2059 for Alternatives 2 and 3 (from 0.5 to approximately 0.04 μg/kg), as compared to about 70 percent for Alternative 4. The increase in surface sediment concentrations after the implementation of the remedy shown in the figures follows from infilling of sediments over the remediated areas from the external sources as well as sediments upriver of the FFS Study Area.

5.2.7 Trajectory Uncertainties

Uncertainty in trajectory forecasts for contaminant concentrations in the bio active layer included using the uncertainty analysis developed for the EMB model combined with additional variability in the distributions developed for the remaining parameters used in the forecast model (*e.g.*, "excess" contaminant half times, mixed layer thickness, sediment deposition rate). Parts B, C, and D of Figures 5-11 through 5-17 present the uncertainty in trajectory forecasts as confidence bounds associated with best estimate, predicted future contaminant concentrations. The most significant finding from the uncertainty analysis is that by 2059 there will be no statistical significant difference between No Action (Alternative 1) and Alternative 4. In addition, Alternatives 2 and 3 are not different from each other by 2059. However, there is a statistically significant difference between Alternatives 2 and 3 versus Alternatives 1 and 4.

5.3 Incorporation of the CPG 2008-2009 Data

The CPG 2008 and 2009 datasets were not available at the time that the Mass Balance Forecast Model analysis was performed. The CPG 2008 and 2009 datasets provide an opportunity to confirm the forecast Lower Passaic River surface sediment concentrations that were presented in the previous sections. In Parts B, C, and D of Figures 5-11 through 5-17, the mean and two standards errors of the measured CPG 2008 and CPG 2009 surface sediment concentrations were added to the Monte Carlo trajectory results. For the contaminants examined, the simulated 2008, and 2009 distributions of the mean surface sediment concentrations fall within the uncertainty of the measurements, except for the simulated 2009 mercury concentration distribution (which plots on the border of the uncertainty range). This agreement between the model forecast and the new CPG data provides a rough validation of the model and the original forecast.

6 SUMMARY

This appendix describes the EMB modeling analysis developed to support the FFS of the lower eight miles of the Lower Passaic River. It consists of an EMB model designed to characterize the fate and transport of contaminants in the Lower Passaic River, as well as a semi-empirical model used to forecast the concentrations of contaminants in Lower Passaic River surface sediment for the FFS remedial alternatives. The summary of the observations are provided below.

6.1 Summary of EMB Results

- Resuspension of legacy sediments represented the single largest contributor of solids to recently-deposited sediments, accounting for 28 to 65 percent of the recent deposition with a best estimate of 48 percent. The Upper Passaic River accounted for about 13 to 49 percent of recently-deposited solids, with a best estimate of 32 percent. Newark Bay accounted for less than 1 to 44 percent, with a best estimate of 14 percent. All the other sources together contribute between 2 and less than 12 percent.
- The mass balance calculated for 2,3,7,8-TCDD, indicates that resuspension accounts for about 87 to 100 percent, with a best estimate of 97 percent of the 2,3,7,8-TCDD observed in recently-deposited sediments in the Lower Passaic River.
- Resuspension contribution of Total PCBs to the Lower Passaic River ranges from 59 to 90 percent with a best estimate of about 81 percent. Upper Passaic River is the most important external source of Total PCB contamination to the Lower Passaic, with a best estimate of 11 percent (range of 4 to 22 percent of the overall mass), while Newark Bay contributes about 7 percent (range of less than 1 to 25 percent) of the overall mass.
- External inputs of PAHs are very important to the PAH mass balance for the system. The Upper Passaic River contribution for benzo[a]pyrene was estimated as 53 percent (ranging from 27 to 70 percent) and for fluoranthene the estimate was 47 percent (ranging from 24 to 64 percent). Resuspension of the historical

inventory accounts for about 39 percent (ranging from 17 to 58 percent) of the PAH contaminant burden of the Lower Passaic River. Newark Bay's PAH contribution ranges from less than 1 percent to 30 percent, with a best estimate of approximately 6 percent. Although higher PAH concentrations were observed in the tributaries and CSOs, comparable to concentrations in the Upper Passaic River, the relatively small solids contributions from the tributaries and CSOs limits their combined contribution to less than 17 percent.

- For 4,4'-DDE, resuspension of the historical inventory contributes between 52 to 88 percent of the mass in recently-deposited sediments, with a best estimate of 78 percent. Newark Bay contributes about 8 percent of 4,4'-DDE mass (ranging from less than 1 to 34 percent) and the Upper Passaic River contributes about 10 percent (ranging from 4 to 21 percent). The combined contribution from tributaries SWOs and CSOs range from 1 to 10 percent, with a best estimate of about 4 percent.
- Similar to 4,4'-DDE, the fate and transport of copper, chromium, mercury, and lead in the Lower Passaic River is dominated by sediment resuspension.
- Overall, the EMB Model identifies the sediments of the Lower Passaic River as an important source of all contaminants of concern and the single most important source of 2,3,7,8-TCDD to the entire Lower Passaic River.

6.2 Summary of Contaminant Forecast Results

- Surface sediment concentrations of 2,3,7,8-TCDD are forecast to decline by 59 percent from 2017 to 2059 under No Action. For the other contaminants, the decline is less than 48 percent. The relatively larger decline in 2,3,7,8-TCDD compared to other contaminants is because the external sources (e.g., Upper Passaic River, tributaries, CSOs/SWOs) are not significant contributors of 2,3,7,8-TCDD to the sediments of the Lower Passaic River.
- The forecasts for Alternatives 2 and 3 show a significant decline over time for most contaminant concentrations when compared to No Action. About a 90 percent reduction in 2,3,7,8-TCDD surface sediment concentrations was

estimated by 2059 for Alternatives 2 and 3. Sediment 2,3,7,8-TCDD concentrations, which originate largely from an internal source (resuspension), are most dramatically reduced by Alternatives 2 and 3. Contaminants such as PAHs, which have a significant external source, are impacted immediately upon remediation, but the improvement wanes as contaminated sediments from external sources are deposited on top of the remediated area and subsequently may resuspend and continue mixing with the river's solids load.

- The surface sediment contaminant concentrations after implementation of Alternatives 2 and 3 are not statistically different from each other by 2059 for the contaminants forecast.
- The trajectory results indicate that by 2059 there will be no statistically significant difference between No Action (Alternative 1) and the focused remedy (Alternative 4). Alternative 4 does not provide the sustained reduction in future concentrations estimated for Alternatives 2 and 3.

7 ACRONYMS

2,3,7,8-TCDD	2,3,7,8-Tetrachlorodibenzo- p-dioxin
4,4'-DDE	4,4'-dichlorodiphenyldichloroethylene
Be-7	Beryllium-7
CMB	Chemical Mass Balance
CPG	Cooperating Parties Group
CSM	Conceptual Site Model
CSO	Combined Sewer Overflow
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
EMB	Empirical Mass Balance
FFS	Focused Feasibility Study
HMW	High Molecular Weight
LMW	Low Molecular Weight
µg/kg	micrograms per kilogram
mg/kg	milligram per kilogram
NME	Normalized Mean Error
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PCDD/F	Polychlorobenzodioxin/furan
ppb	parts per billion
R^2	coefficient of determination of regression line fits
RI	Remedial Investigation
RM	River Mile
RPI	Rensselaer Polytechnic Institute
SWO	Stormwater Outfall
TOC	Total Organic Carbon
Total DDx	the sum of the 4,4'-dichlorodiphenyldichloroethane (4-4'-DDD), 4,4'-dichlorodiphenyldichloroethylene (4,4'-DDE) and 4,4'-Dichlorodiphenyltrichloroethane (4,4'-DDT) concentrations

Total TCDD	Total Tetrachlorodibenzodioxin
TSI	Tierra Solutions, Inc.
USEPA	United State Environmental Protection Agency

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TABLES

Table 3-1: EMB Model Optimization Parameters

Chemical Class	Chemical Name
Metals	Chromium
	Copper
	Lead
	Mercury
PCDD/F	2,3,7,8-TCDD
	Total TCDD
Pesticides	4,4'-DDE
	gamma-Chlordane
PAH	Benzo[a]pyrene
	Fluoranthene
PCB Congeners and Co-Elutions	Total PCB
Other Parameters	Total Organic Carbon (TOC)
	Iron

Table 3-2: Additional Parameters Used for EMB Model Evaluation

Chemical Class	Chemical Name
Metals	Arsenic
	Cadmium
	Cobalt
	Nickel
	Zinc
PAH Compounds	Benz[a]anthracene
	Chrysene
	Indeno[1,2,3-cd]pyrene
	Pyrene

Table 3-3: Average Resuspension (Lower Passaic River) Concentrations for Selected Contaminants (0-6 inch Surface Sediment Samples)

Analyte	Resuspension (Lower Passaic River) Concentrations [a]
Arsenic (mg/kg)	11
Cadmium (mg/kg)	5.1
Chromium (mg/kg)	150
Cobalt (mg/kg)	11
Copper (mg/kg)	230
Lead (mg/kg)	330
Mercury (mg/kg)	3.3
Nickel (mg/kg)	45
Zinc (mg/kg)	560
gamma-Chlordane (µg/kg)	26
4,4'-DDE (µg/kg)	66
2,3,7,8-TCDD (ng/kg)	810
Total TCDD (ng/kg)	960
Total PCB (ug/kg)	2,100
Benz[a]anthracene (mg/kg)	2.5
Benzo[a]pyrene (mg/kg)	2.4
Chrysene (mg/kg)	3.1
Fluoranthene (mg/kg)	5.2
Indeno[1,2,3-cd]pyrene (mg/kg)	0.9
Pyrene (mg/kg)	5.5
Iron (mg/kg)	25,000
TOC (%)	10

Concentrations rounded to two significant figures.

Note:
a: Data Source: 1995 TSI 0-6 inch surface sediment samples RM1 to RM7 were used for average resuspension calculation.

Table 3-4: Newark Bay Northern End and Southern End Average Concentrations for Selected Contaminants

Analyte	Average Northern Concentration [b]	Average Southern Concentration [c]
Arsenic (mg/kg)	11	10
Cadmium (mg/kg)	1.5	0.63
Chromium (mg/kg)	110	67
Cobalt (mg/kg)	10	10
Copper (mg/kg)	130	82
Lead (mg/kg)	125	77
Mercury (mg/kg)	2.2	0.93
Nickel (mg/kg)	35	33
Zinc (mg/kg)	250	160
gamma-Chlordane (µg/kg)[a]	4.8	3.8
4,4'-DDE (µg/kg)	25	14
2,3,7,8-TCDD (ng/kg)	86	23
Total TCDD (ng/kg)	180	65
Total PCB (ug/kg)	580	260
Benz[a]anthracene (mg/kg)	1.5	0.44
Benzo[a]pyrene (mg/kg)	1.8	0.47
Chrysene (mg/kg)	1.7	0.44
Fluoranthene (mg/kg)	2.4	0.60
Indeno[1,2,3-cd]pyrene (mg/kg)	0.8	0.32
Pyrene (mg/kg)	2.7	0.65
Iron (mg/kg)	30,000	30,000
TOC (%)	2.6	1.7

Concentrations rounded to two significant numbers.

Note:
a. Newark Bay samples from the 2005 sampling event were reported non-detect for gamma-Chlordane. The value used here is from Phase 2 Dataset, 2007.
b. The samples used to delineate the northern Newark Bay end member were NB01SED46, NB01SED47, NB01SED52, NB01SED52 (dup), NB01SED55 and NB01SED61 from Phase 1 dataset and NB02SED078, NB02SED094, NB02SED104, NB02SED106, and NB02SED107 from Phase 2 dataset.
c. The five samples used to delineate the southern Newark Bay end member were NB01SED017, NB01SED021, NB01SED024, NB01SED030 and NB01SED031 from Phase 1 dataset.

Table 3-5: Upper Passaic River Recently-Deposited Surface Sediment Concentrations for Selected Contaminants

Analyte	Upper Passaic River Concentrations [a]
Arsenic (mg/kg)	2.9
Cadmium (mg/kg)	1.5
Chromium (mg/kg)	31
Cobalt (mg/kg)	8.8
Copper (mg/kg)	63
Lead (mg/kg)	130
Mercury (mg/kg)	0.72
Nickel (mg/kg)	19
Zinc (mg/kg)	290
gamma-Chlordane (µg/kg)	23
4,4'-DDE (µg/kg)	13
2,3,7,8-TCDD (ng/kg)	1.9
Total TCDD (ng/kg)	42
Total PCB (ug/kg)	420
Benz[a]anthracene (mg/kg)	4.7
Benzo[a]pyrene (mg/kg)	5.6
Chrysene (mg/kg)	6.4
Fluoranthene (mg/kg)	9.1
Indeno[1,2,3-cd]pyrene (mg/kg)	3.5
Pyrene (mg/kg)	9.1
Iron (mg/kg)	16,000
TOC (%)	3.7

Concentrations rounded to two significant figures.

Note:
a: Samples from 2008 USEPA suspended-phase high flow storm sampling event were used to calculate the average concentrations. Only recently deposited surface sediment samples were used in the above calculation. Two water column suspended matter samples LPRP-LVCG-DDL-000004 and LPRP-LVCG-DDL-000006 were not used. The samples used to delineate the Upper Passaic River were LPRP-SCSH-DDL-000018, LPRP-SCSH-DDL- 000068, LPRP-SCSH-DDL- 000143, LPRP-SCSH-DDL- 000153, LPRP-SCSH-PSR-001607, LPRP-SCSH-PSR- 001602, LPRP-SCSH-PSR-001604, LPRP-SCSH-PSR- 001590, LPRP-SCSH-PSR- 001663, LPRP-SCSH- PSR-001579, and LPRP-SCSH-PSR- 001589.

Table 3-6: Tributary Average Concentrations for Selected Contaminants [a]

Analyte	Saddle River [b]	Third River [c]	Second River [d]
Arsenic (mg/kg)	3.6	5.7	3.4
Cadmium (mg/kg)	0.41	1.4	0.75
Chromium (mg/kg)	20	35	25
Cobalt (mg/kg)	4.4	5.7	4.9
Copper (mg/kg)	43	68	42
Lead (mg/kg)	57	150	170
Mercury (mg/kg)	0.1	0.48	0.26
Nickel (mg/kg)	10	20	21
Zinc (mg/kg)	150	260	220
gamma-Chlordane (μg/kg)	55	77	27
4,4'-DDE (μg/kg)	19	46	26
2,3,7,8-TCDD (ng/kg)	2.9	2	0.9
Total TCDD (ng/kg)	25	24	11
Total PCB (ug/kg)	370	400	100
Benz[a]anthracene (mg/kg)	2.8	3.4	2.92
Benzo[a]pyrene (mg/kg)	3.7	4.3	3.3
Chrysene (mg/kg)	4.6	5.6	4.2
Fluoranthene (mg/kg)	8.7	9.5	8.4
Indeno[1,2,3-cd]pyrene (mg/kg)	2.8	3.3	2.5
Pyrene (mg/kg)	7.3	8	7
Iron (mg/kg)	11,000	14,000	14,000
TOC (%)	4.1	5.5	4.5

Concentrations rounded to two significant figures.

Note:
a: Samples from 2008 USEPA suspended-phase high flow storm sampling event were used to calculate the average concentrations. Only recently deposited surface sediment samples were used in the above calculation.
b: The samples used to delineate the average Saddle River concentrations were LPRP-SCSH-SDR-000001, LPRP-SCSH-SDR-000005, LPRP-SCSH-SDR-000006, LPRP-SCSH-SDR-000007, LPRP-SCSH-SDR-000003, and LPRP-SCSH-SDR- 000004. Samples were from 2008 USEPA suspended-phase high flow storm sampling event.
c: The samples used to delineate the average Third River concentrations were LPRP-SCSH-THR- 000001, LPRP-SCSH-THR-000002, LPRP-SCSH-THR-000003, and LPRP-SCSH-THR- 000006.
d: The samples used to delineate the average Second River concentrations were LPRP-SCSH-SCR-000001, LPRP-SCSH-SCR-000004, LPRP-SCSH-SCR-000005, and LPRP-SCSH-SCR- 000006. Samples were from 2008 USEPA suspended-phase high flow storm sampling event.

Table 3-7: Average CSO and SWO Concentrations for Selected Contaminants

Analyte	Average CSO Concentrations [a]	Average SWO Concentrations
Arsenic (mg/kg)	6.6	15
Cadmium (mg/kg)	2.1	1.9
Chromium (mg/kg)	68	100
Cobalt (mg/kg)	8.3	16
Copper (mg/kg)	310	260
Lead (mg/kg)	390	350
Mercury (mg/kg)	0.99	0.75
Nickel (mg/kg)	49	62
Zinc (mg/kg)	850	820
gamma-Chlordane (µg/kg)	30	120
4,4'-DDE (µg/kg)	25	60
2,3,7,8-TCDD (ng/kg)	4.2	20
Total TCDD (ng/kg)	73	123
Total PCB (ug/kg)	940	400
Benz[a]anthracene (mg/kg)	1.9	6.6
Benzo[a]pyrene (mg/kg)	2.2	9.7
Chrysene (mg/kg)	3.8	25
Fluoranthene (mg/kg)	5.7	39
Indeno[1,2,3-cd]pyrene (mg/kg)	2.1	9.2
Pyrene (mg/kg)	5.6	32
Iron (mg/kg)	22,000	42,000
TOC (%)	30	19

Concentrations rounded to two significant figures.

Note:
a: The samples used to delineate the average CSO concentrations were LPRP-LVCG-PSR-000399, LPRP-LVCG-PSR-000400, LPRP-LVCG-PSR-000401, LPRP-LVCG-PSR-000402, LPRP-LVCG-PSR-000403, LPRP-LVCG-PSR-000404, LPRP-LVCG-PSR-000405, LPRP-LVCG-PSR-000406, LPRP-LVCG-PSR-000407, LPRP-LVCG-PSR-000423, LPRP-LVCG-PSR-000424, LPRP-LVCG-PSR-000433, LPRP-LVCG-PSR-000434, and LPRP-LVCG-PSR-000435. Samples were from 2008 USEPA suspended-phase high flow storm sampling event.
b: The samples used to delineate the average SWO concentrations were LPRP-LVCG-PSR-000409, LPRP-LVCG-PSR-000410, LPRP-LVCG-PSR-000411, LPRP-LVCG-PSR-000412, LPRP-LVCG-PSR-000413, LPRP-LVCG-PSR-000414, LPRP-LVCG-PSR-000416, LPRP-LVCG-PSR-000417, LPRP-LVCG-PSR-000418, LPRP-LVCG-PSR-000419, LPRP-LVCG-PSR-000420, LPRP-LVCG-PSR-000421, LPRP-LVCG-PSR-000425, LPRP-LVCG-PSR-000426, LPRP-LVCG-PSR-000427, LPRP-LVCG-PSR-000428, LPRP-LVCG-PSR-000429, and LPRP-LVCG-PSR-000432. Samples were from 2008 USEPA suspended-phase high flow storm sampling event.

Table 3-8: Average Lower Passaic River Recently-Deposited (Be-7 Bearing) Sediment Concentrations for Selected Contaminants

Analyte	Average Main stem (RM2 – RM12) Concentration [a]
Arsenic (mg/kg)	8.0
Cadmium (mg/kg)	3.6
Chromium (mg/kg)	110
Cobalt (mg/kg)	8.6
Copper (mg/kg)	160
Lead (mg/kg)	210
Mercury (mg/kg)	1.9
Nickel (mg/kg)	32
Zinc (mg/kg)	490
gamma-Chlordane (µg/kg)	36
4,4'-DDE (µg/kg)	52
2,3,7,8-TCDD (ng/kg)	370
Total TCDD (ng/kg)	530
Total PCB (ug/kg)	1,200
Benz[a]anthracene (mg/kg)	2.8
Benzo[a]pyrene (mg/kg)	3.6
Chrysene (mg/kg)	4.1
Fluoranthene (mg/kg)	5.9
Indeno[1,2,3-cd]pyrene (mg/kg)	2.5
Pyrene (mg/kg)	5.8
Iron (mg/kg)	26,000
TOC (%)	6.3

Concentrations rounded to two significant figures.

Note:
a: Data source: Be-7 bearing sediment samples from 2007-2008 Malcolm Pirnie Sediment Sampling Program and 2005-2006 High Resolution Coring Program.

Table 4-1: Contaminant Burden Attributed to Resuspension

Analyte	Percent of Contaminant Burden in Recently Deposited Sediments Attributed to Resuspension and Confidence Interval
Chromium	≈ 74 (44 to 88)
Copper	≈ 72 (45 to 85)
Lead	≈ 71 (48 to 83)
Mercury	≈ 75 (43 to 88)
gamma-Chlordane	≈ 52 (32 to 70)
4,4'-DDE	≈ 78 (52 to 88)
2,3,7,8-TCDD	≈ 97 (87 to 100)
Total TCDD	≈ 92 (76 to 97)
Total PCB	≈ 81 (59 to 90)
Benzo[a]pyrene	≈ 33 (17 to 52)
Fluoranthene	≈ 40 (21 to 58)
Iron	≈ 54 (29 to 72)
TOC	≈ 72 (48 to 83)

Table 4-2: Summary of Solids Contribution Results for Best Estimate Scenarios

Solids and Analytes	Resuspension	Newark Bay	Upper Passaic River	Saddle River	Second River / Storm Water Outfall	Third River	Combined Sewer Overflow
Solids	48%	14%	32%	4%	1%	1%	0.5%
Copper	72%	12%	14%	1%	0.4%	0.3%	1%
Chromium	74%	15%	10%	1%	0.4%	0.3%	0.3%
Iron	54%	18%	24%	2%	1%	1%	0.5%
Mercury	75%	14%	11%	0.2%	0.2%	0.2%	0.2%
Lead	71%	7%	19%	1%	1%	0.5%	1%
gamma-Chlordane	52%	3%	32%	8%	2%	2%	1%
4,4'-DDE	78%	8%	10%	2%	1%	1%	0.3%
2,3,7,8-TCDD	97%	3%	0.1%	0.03%	0.003%	0.004%	0.005%
Total TCDD	92%	5%	3%	0.2%	0.03%	0.04%	0.07%
Total PCB	81%	7%	11%	1%	0.1%	0.3%	0.4%
Benzo(a)pyrene	33%	7%	53%	4%	2%	1%	0.3%
Fluoranthene	40%	5%	47%	5%	2%	1%	0.4%
TOC	72%	5%	17%	2%	1%	1%	2%

Table 4-3: Summary of Solids Contribution Results for SWO Sensitivity Scenarios

Solids and Analytes	Resuspension	Newark Bay	Upper Passaic River	Saddle River	Second River	Third River	Storm Water Outfall	Combined Sewer Overflow
Solids	47%	17%	31%	3%	0%	1%	1%	0%
Copper	69%	14%	13%	1%	0%	0%	2%	1%
Chromium	70%	18%	9%	1%	0%	0%	1%	0%
Iron	51%	22%	22%	2%	0%	0%	2%	0%
Mercury	72%	17%	10%	0%	0%	0%	0%	0%
Lead	69%	9%	18%	1%	0%	0%	2%	1%
gamma-Chlordane	50%	3%	30%	8%	0%	2%	7%	1%
4,4'-DDE	76%	10%	10%	2%	0%	1%	2%	0%
2,3,7,8-TCDD	96%	4%	0%	0%	0%	0%	0%	0%
Total TCDD	91%	6%	3%	0%	0%	0%	0%	0%
Total PCB	79%	8%	11%	1%	0%	0%	0%	0%
Benzo(a)pyrene	33%	8%	51%	4%	0%	1%	3%	0%
Fluoranthene	37%	6%	43%	5%	0%	1%	7%	0%
TOC	70%	6%	16%	2%	0%	1%	3%	2%

Table 4-4: Summary of Solids Contribution Results for Relaxed Solids Constraint Sensitivity Scenarios

Solids and Analytes	Resuspension	Newark Bay	Upper Passaic River	Saddle River	Second River / Storm Water Outfall	Third River	Combined Sewer Overflow
Solids	42%	20%	32%	4%	2%	1%	0%
Copper	65%	18%	14%	1%	1%	0%	1%
Chromium	65%	23%	10%	1%	0%	0%	0%
Iron	46%	27%	23%	2%	1%	0%	0%
Mercury	67%	21%	11%	0%	0%	0%	0%
Lead	65%	12%	19%	1%	2%	1%	1%
gamma-Chlordane	48%	4%	33%	9%	2%	3%	1%
4,4'-DDE	72%	13%	11%	2%	1%	1%	0%
2,3,7,8-TCDD	95%	5%	0%	0%	0%	0%	0%
Total TCDD	89%	8%	3%	0%	0%	0%	0%
Total PCB	76%	10%	12%	1%	0%	0%	0%
Benzo(a)pyrene	30%	11%	53%	4%	2%	1%	0%
Fluoranthene	36%	8%	47%	5%	3%	1%	0%
TOC	67%	8%	18%	2%	1%	1%	2%

Table 4-5: Comparison of 2008 Tributary and Dundee Dam Measured Surface Sediment Concentrations with Monte Carlo Simulated Model Inputs

Contaminant	Units	Second River			Third River			Saddle River		
		Monte Carlo Model Simulated Range of Possible Concentrations	USEPA 2008 Surface Grab (0-1 inch) and Sediment Trap	CPG 2008 Surface Results (Measured	Monte Carlo Model Simulated Range of Possible Concentrations	USEPA 2008 Surface Grab (0-1 inch) and Sediment Trap	CPG 2008 Surface Results (Measured 0-6 inches)	Monte Carlo Model Simulated Range of Possible Concentrations	USEPA 2008 Surface Grab (0-1 inch) and Sediment Trap	CPG 2008 Surface Results (Measured 0-6 inches)
			Average ± Standard Deviation (Range) Count = 4	Average ± Standard Deviation (Range) Count = 3 (PCBs, Metals, PAHs, Pesticides) Count = 2 (Dioxins)		Average ± Standard Deviation (Range) Count = 3	Average ± Standard Deviation (Range) Count = 4		Average ± Standard Deviation (Range) Count = 4 (Dioxins, PCBs, PAHs, Pesticides) Count = 6 (Metals)	Average ± Standard Deviation (Range) Count = 3
2,3,7,8-TCDD	ng/kg	0.1 to 1.8	0.92 ± 0.98 (0.1 to 1.8)	4.2 ± 5.9 (0.030 to 8.3)	1.7 to 2.4	2.0 ± 0.35 (1.7 to 2.5)	48 ± 83 (0.062 to 144)	1.2 to 6.7	2.9 ± 2.6 (1.2 to 6.7)	0.075 ± 0.039 (0.033 to 0.11)
Total TCDD	ng/kg	3 to 22.8	11 ± 8.4 (3.0 to 23)	3.1 ± 3.2 (0.89 to 5.4)	13.3 to 30.7	24 ± 7.8 (13 to 31)	31 ± 54 (0.040 to 93)	18.7 to 34	25 ± 6.8 (19 to 34)	1.6 ± 1.2 (0.37 to 2.7)
Total PCB	mg/kg	0 to 0.2	0.10 ± 0.054 (0.043 to 0.17)	0.034 ± 0.023 (0.011 to 0.056)	0.1 to 1	0.40 ± 0.43 (0.12 to 1.0)	0.092 ± 0.12 (0.0032 to 0.23)	0 to 1.1	0.37 ± 0.51 (0.050 to 1.1)	0.10 ± 0.076 (0.038 to 0.19)
Mercury	mg/kg	0.1 to 0.5	0.26 ± 0.15 (0.097 to 0.46)	0.90 ± 0.045 (0.051 to 0.14)	0.3 to 0.7	0.48 ± 0.19 (0.29 to 0.67)	0.18 ± 0.13 (0.085 to 0.32)	0.1 to 0.2	0.10 ± 0.038 (0.063 to 0.17)	0.12 ± 0.11 (0.033 to 0.24)
Chromium	mg/kg	18.2 to 40.9	25 ± 11 (18 to 41)	11 ± 1.6 (9.3 to 12)	27.2 to 42.9	35 ± 6.5 (27 to 43)	29 ± 14 (13 to 37)	14.8 to 36.5	20 ± 8.4 (15 to 37)	21 ± 7.9 (13 to 29)
Benzo[a]pyrene	ug/kg	792 to 7,089	3,300 ± 2,700 (790 to 7,100)	220 ± 150 (70 to 370)	3,810 to 4,930	4,300 ± 500 (3,800 to 4,900)	1,300 ± 1,300 (0.018 to 2,600)	2,600 to 4,799	3,700 ± 1,100 (2,600 to 4,800)	1,100 ± 420 (670 to 1,500)
Fluoranthene	ug/kg	1,770 to 17,599	8,400 ± 6,900 (1,800 to 18,000)	400 ± 350 (75 to 770)	8,220 to 11,099	9,500 ± 1,400 (8,200 to 11,000)	2,800 ± 3,100 (1.9 to 6,100)	5,832 to 11,499	8,700 ± 3,200 (5,800 to 12,000)	1,500 ± 1,400 (90 to 2,800)
4,4'-DDE	ug/kg	6.6 to 54.7	26 ± 20 (6.6 to 55)	4.2 ± 3.7 (1.6 to 8.5)	35 to 60.1	46 ± 11 (35 to 60)	15 ± 14 (0.12 to 28)	12.7 to 28	19 ± 6.8 (13 to 28)	4.7 ± 1.5 (3.7 to 6.4)
gamma-Chlordane	ug/kg	12.1 to 54.2	27 ± 19 (12 to 54)	3.4 ± 0.91 (2.4 to 4.1)	33.9 to 139	77 ± 45 (34 to 140)	31 ± 28 (0.21 to 55)	31.7 to 77.6	55 ± 23 (32 to 78)	12 ± 1.0 (11 to 13)

Notes:

1. The nondetect values are presented as half the detection limit.
2. Dundee Dam samples are repeated for completeness.
3. CPG 2008 2,3,7,8-TCDD values are presented corrected using the correction factor.
4. CPG 2008 and 2009 uses lab generated sum of PCB congeners.

Measured average surface sediment concentration is higher than the simulated concentration range
Measured average surface sediment concentration is less than the simulated concentration range

Table 4-5: Comparison of 2008 Tributary and Dundee Dam Measured Surface Sediment Concentrations with Monte Carlo Simulated Model Inputs

Contaminant	Units	Dundee Dam				
		Monte Carlo Model Simulated Range of Possible Concentrations	USEPA 2008 Surface Grab (0-1 inch) and Sediment Trap	USEPA High Resolution Cores (Measured Composite 0-1 inch or 2 cm)	USEPA High Resolution Cores (Calculated Length Weighted Average 0-6.3 inches or 16 cm)	CPG 2008 Surface Results (Measured 0-6 inches)
			Average ± Standard Deviation (Range) Count = 8 (Dioxins, PCBs, PAHs, Pesticides) Count = 10 (Metals)	Average ± Standard Deviation (Range) Count = 4	Average ± Standard Deviation (Range) Count = 3 (Dioxins, PCBs, and PAHs) Count = 4 (Metals and Pesticides)	Average ± Standard Deviation (Range) Count = 6
2,3,7,8-TCDD	ng/kg	1 to 2.9	1.8 ± 0.56 (1.0 to 2.9)	2.5 ± 0.59 (1.9 to 3.0)	10 ± 11 (3.2 to 24)	6.2 ± 15 (0.038 to 37)
Total TCDD	ng/kg	26 to 73.4	41 ± 16 (26 to 73)	70 ± 22 (37 to 87)	170 ± 99 (70 to 270)	150 ± 330 (4.0 to 810)
Total PCB	mg/kg	0.2 to 0.7	0.34 ± 0.19 (0.21 to 0.69)	0.60 ± 0.090 (0.50 to 0.69)	2.4 ± 1.8 (0.46 to 4.0)	1.1 ± 2.0 (0.083 to 5.1)
Mercury	mg/kg	0.4 to 1.8	0.75 ± 0.40 (0.46 to 1.8)	1.5 ± 0.71 (0.72 to 2.2)	3.1 ± 1.4 (2.2 to 5.1)	2.4 ± 3.9 (0.40 to 10)
Chromium	mg/kg	20.6 to 51.4	32 ± 9.8 (21 to 51)	41 ± 16 (23 to 58)	73 ± 17 (57 to 94)	31 ± 18 (12 to 55)
Benzo[a]pyrene	ug/kg	3,471 to 9,749	5,400 ± 1,400 (3,500 to 7,200)	7,800 ± 3,800 (3,500 to 13,000)	15,000 ± 11,000 (5,700 to 29,000)	26,000 ± 27,000 (620 to 53,000)
Fluoranthene	ug/kg	5,950 to 16,197	8,800 ± 1,900 (6,000 to 12,000)	7,600 ± 2,100 (6,100 to 11,000)	14,000 ± 6,000 (8,900 to 22,000)	42,000 ± 47,000 (850 to 100,000)
4,4'-DDE	ug/kg	7.5 to 25.6	13 ± 5.6 (7.5 to 26)	18 ± 5.2 (14 to 26)	42 ± 30 (6.5 to 62)	40 ± 84 (1.1 to 210)
gamma-Chlordane	ug/kg	13.5 to 47	24 ± 9.9 (15 to 47)	34 ± 11 (21 to 47)	34 ± 34 (10 to 73)	11 ± 10 (1.6 to 29)

Notes:
1. The nondetect values are presented as half the detection limit.
2. Dundee Dam samples are repeated for completeness.
3. CPG 2008 2,3,7,8-TCDD values are presented corrected using the correction factor.
4. CPG 2008 and 2009 uses lab generated sum of PCB congeners.

Measured average surface sediment concentration is higher than the simulated concentration range
Measured average surface sediment concentration is less than the simulated concentration range

Table 5-1: Comparison of the Average 1980s Concentrations and 2005 Surface Sediment Concentrations for Selected Contaminants

Analyte	Average 1980s Decadal Concentration	Average 2005 Surface Sediment Concentration
Mercury (mg/kg)	3.3	1.8
Lead (mg/kg)	320	210
Copper (mg/kg)	180	150
gamma-Chlordane (µg/kg)	85	70
Dieldrin (µg/kg)	2.4	5.8
4,4'-DDE (µg/kg)	110	54
2,3,7,8-TCDD (ng/kg)[a]	560	430
Total PCB (µg/kg)[a]	2,500	1,000
LMW PAH (mg/kg)	10	10
HMW PAH (mg/kg)	25	28

Concentrations rounded to two significant figures.

Note:
a: Average decadal concentration for three river locations (RM1.4, RM2.2, and RM11)

Table 5-2: Contaminant Half Times for "Excess Concentration" in Lower Passaic River Sediments Based on High Resolution Cores from 2005 and Surface Samples in 2007 (See Text for Explanation)

Analyte	Half Time (Confidence Interval) 1980-2007 (years)
Mercury (mg/kg)	34 (19-173)
Lead (mg/kg)	39.5 (23-151)
Copper (mg/kg)	57 (30.7-405)
gamma-Chlordane (µg/kg)[a]	99
4,4'-DDE (µg/kg)	19 (13-33)
Dieldrin (µg/kg)	No Applicable[b]
2,3,7,8-TCDD (ng/kg)	25 (14-101)
Total PCB (µg/kg)	26 (16-61)
HMW PAH (mg/kg)[1]	44
LMW PAH (mg/kg)	63

Note:
a: No statistically significant trend with time. Future concentrations are taken as constant.
b: Increasing trend with time. Half time for decline cannot be determined.

Table 5-3a: Reduction in Best Estimate Forecasted Surface Sediment Concentrations in 2059 relative to 2017

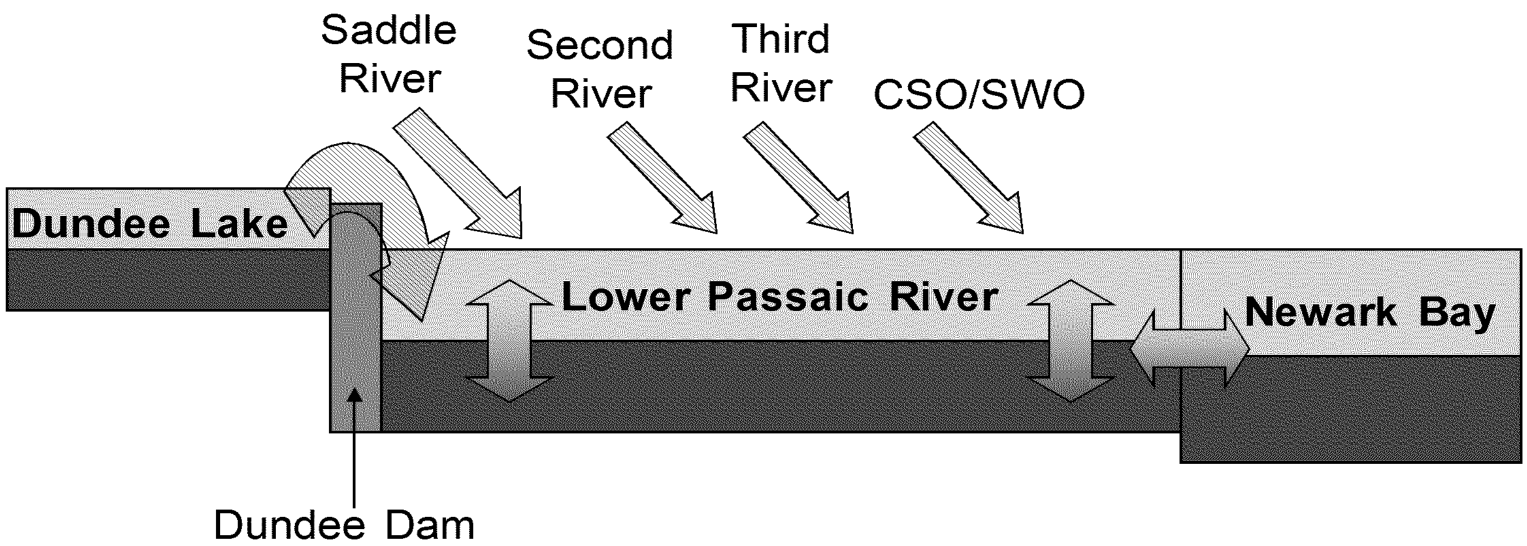
Contaminant	Alternative 1	Alternative 2	Alternative 3	Alternative 4
gamma-Chlordane	0%	38%	32%	12%
Copper	23%	63%	59%	37%
4,4'-DDE	50%	78%	75%	60%
2,3,7,8-TCDD	59%	91%	90%	71%
Mercury	37%	72%	68%	49%
Lead	28%	65%	61%	41%
Total PCB	48%	79%	76%	59%
HMW PAH	0%	34%	27%	10%

Table 5-3b: Best Estimate Forecasted Surface Sediment Concentrations in 2017 and 2059

Contaminant	Concentrations in 2017 for All Alternatives	Concentrations in 2059			
		Alternative 1	Alternative 2	Alternative 3	Alternative 4
gamma-Chlordane	23	24	15	16	21
Copper	160	130	60	70	100
4,4'-DDE	50	30	10	10	20
2,3,7,8-TCDD	0.5	0.2	0.04	0.05	0.1
Mercury	2.5	1.5	0.7	0.8	1.2
Lead	260	180	90	100	150
TotalPCB	1,590	820	340	380	650
HMWPAH	43,000	43,000	28,000	31,000	38,000

Note: Concentration is rounded to 2 significant digits.

FIGURES



Legend

Water

Sediment

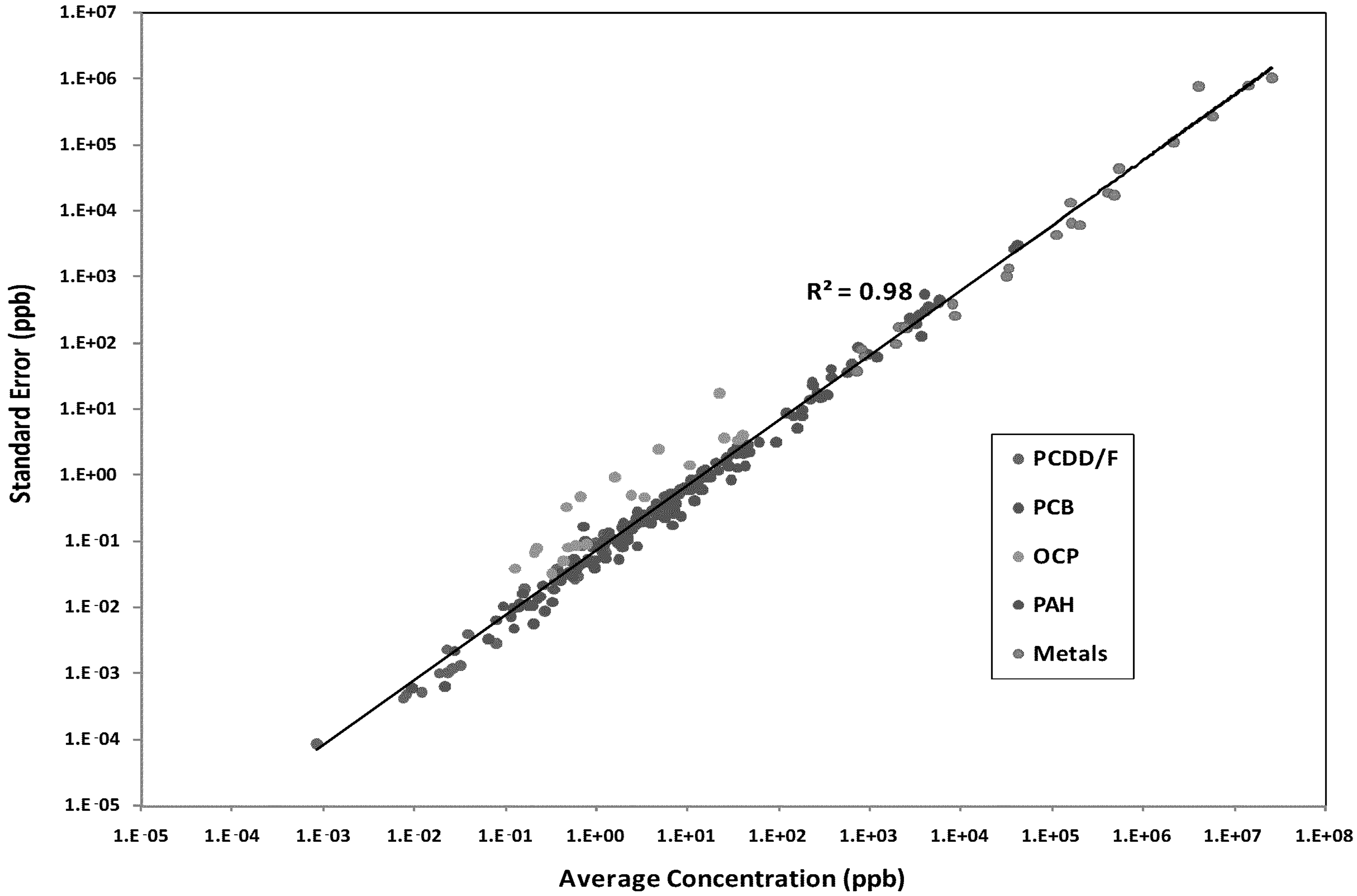
Notes

Sources of Model for the Lower Passaic River Empirical Mass Balance

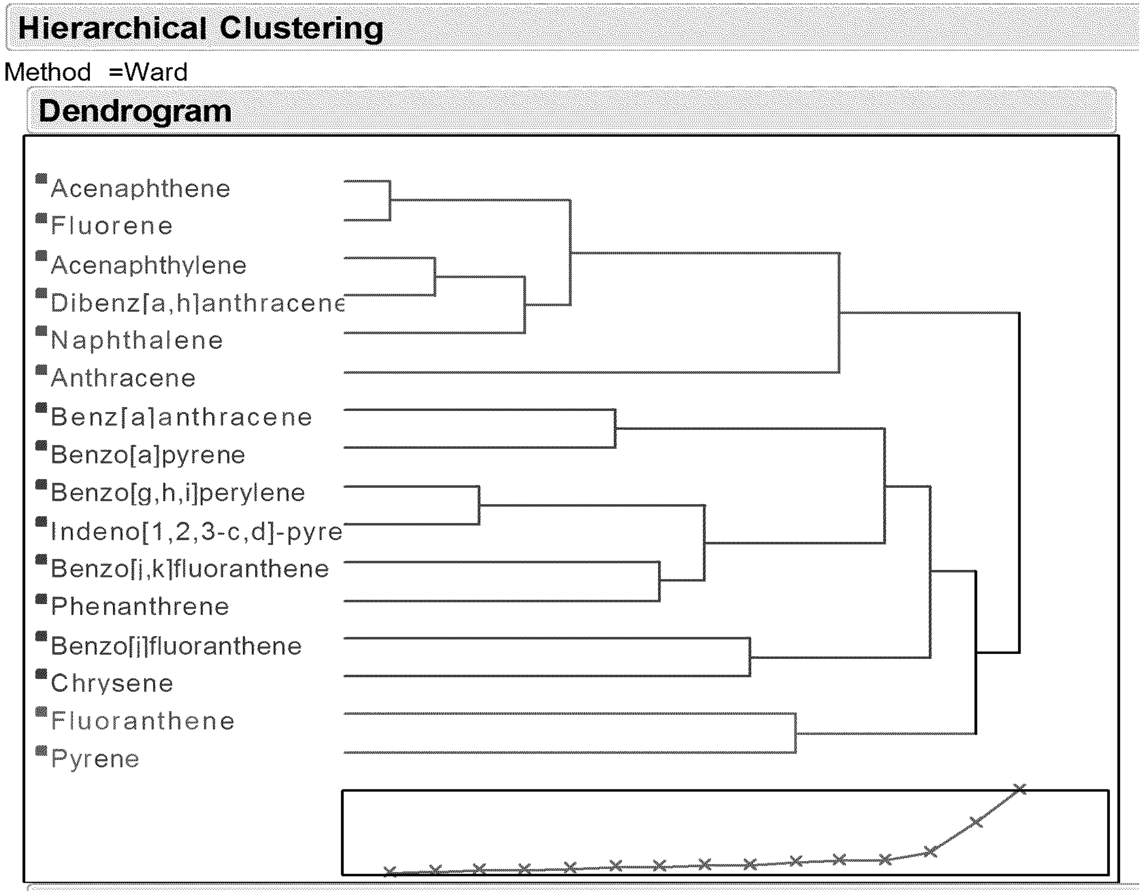
Lower Eight Miles of the Lower Passaic River

Figure 3-1

2014



	Relationship between Average Contaminant Concentration and Standard Error for the Recently-Deposit ed Sediments in the Main Stem Lower Passaic River *Lower Eight Miles of the Lower Passaic River*	Figure 3-2 2014

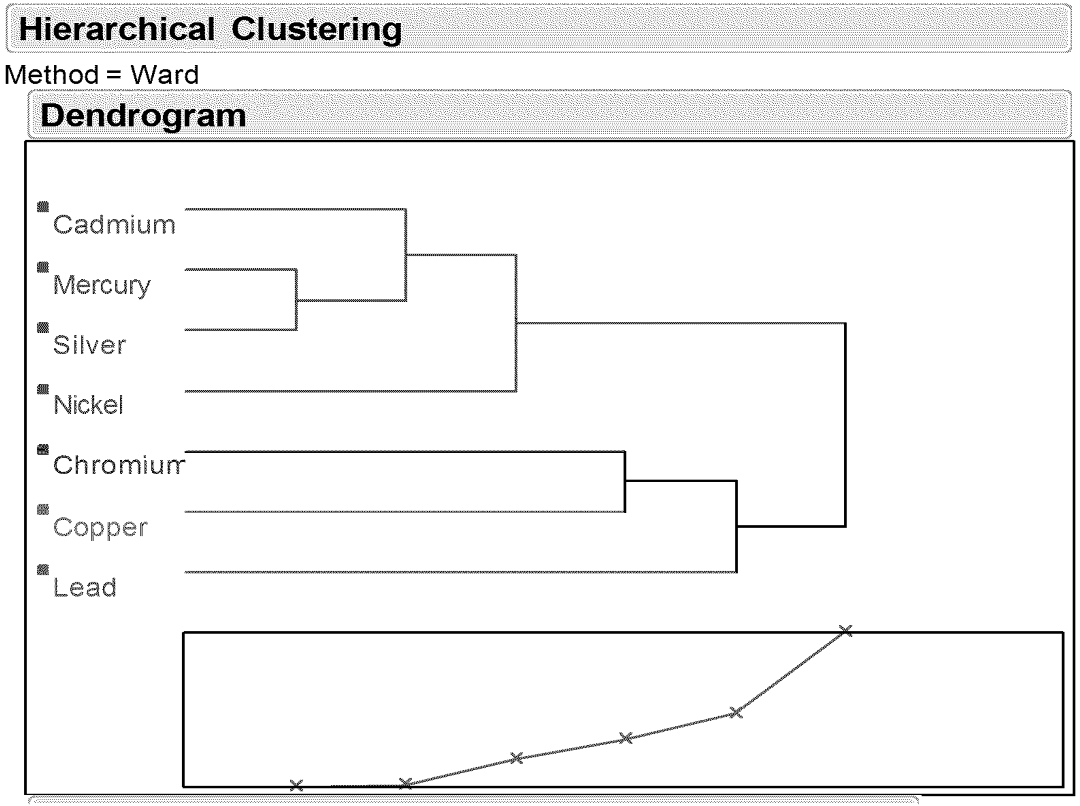


Cluster Analysis for PAHs

Lower Eight Miles of the Lower Passaic River

Figure 3-3

2014

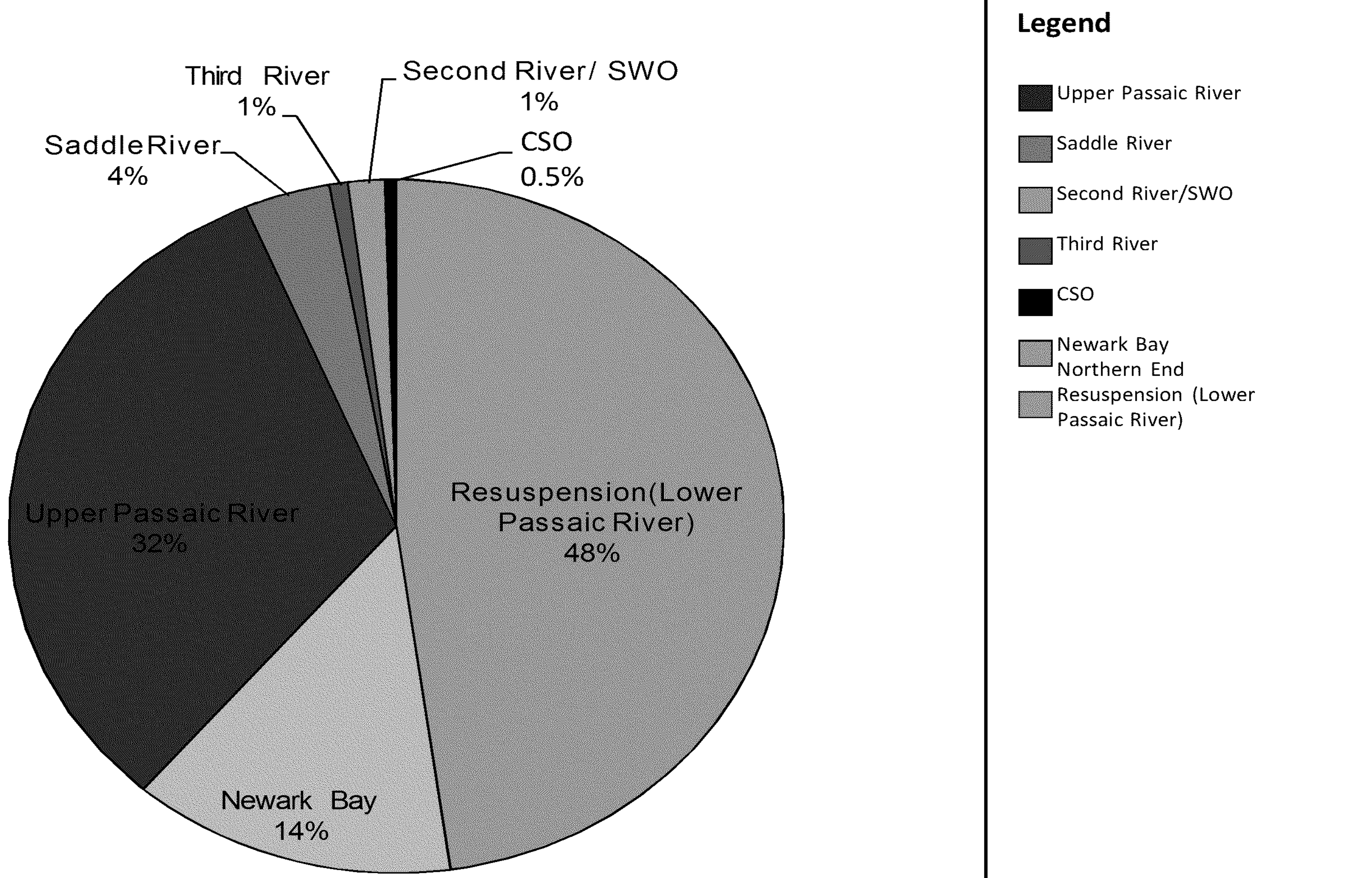


Cluster Analysis for Metals

Lower Eight Miles of the Lower Passaic River

Figure 3-4

2014

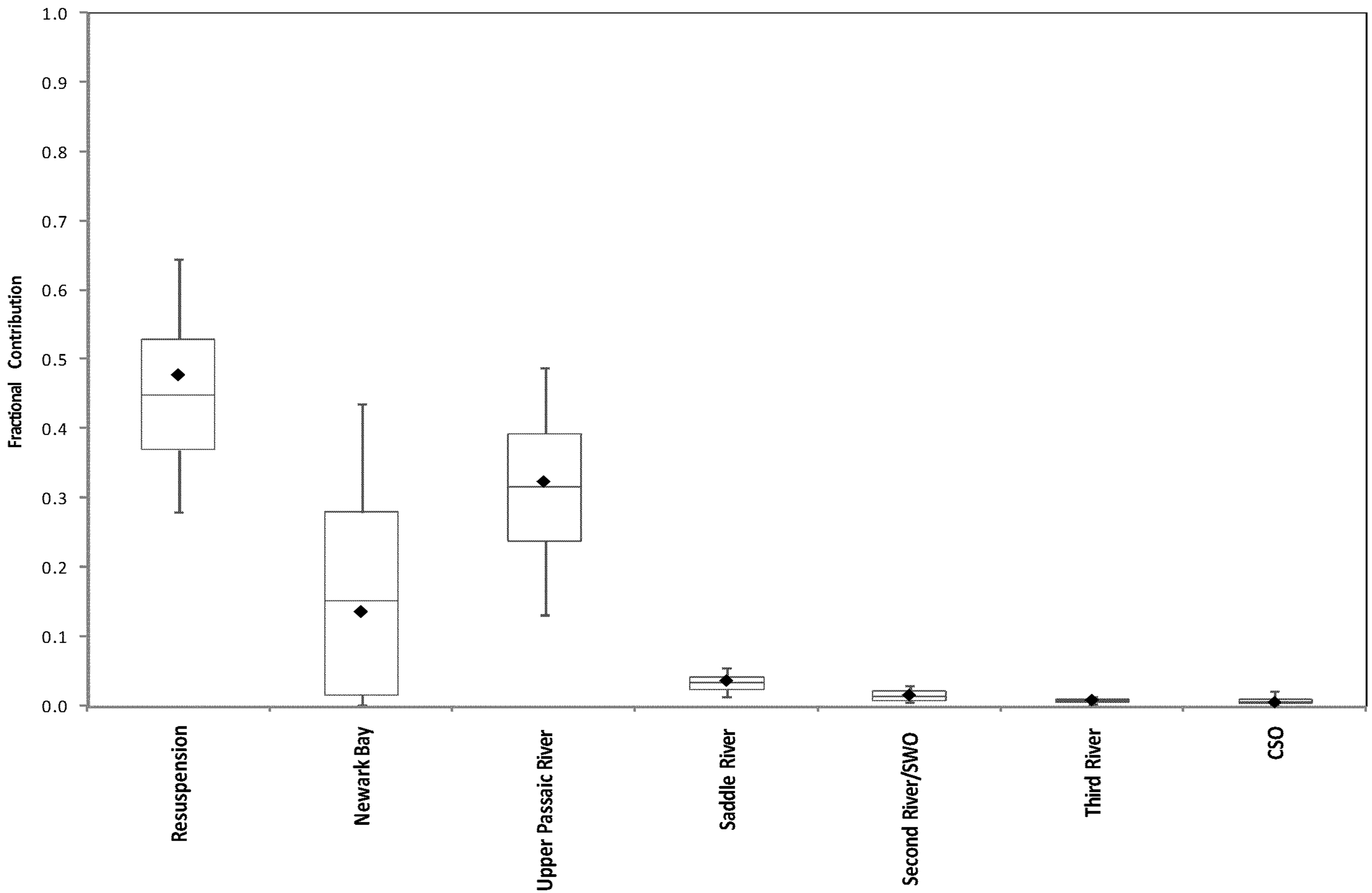


Best Estimate of Relative Solids Contribution to the Lower Passaic River
Estimated by the EMB Model

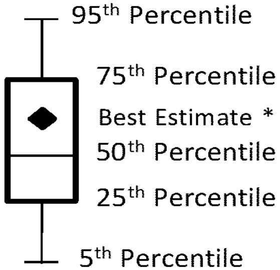
Lower Eight Miles of the Lower Passaic River

Figure 4-1

2014



Legend



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

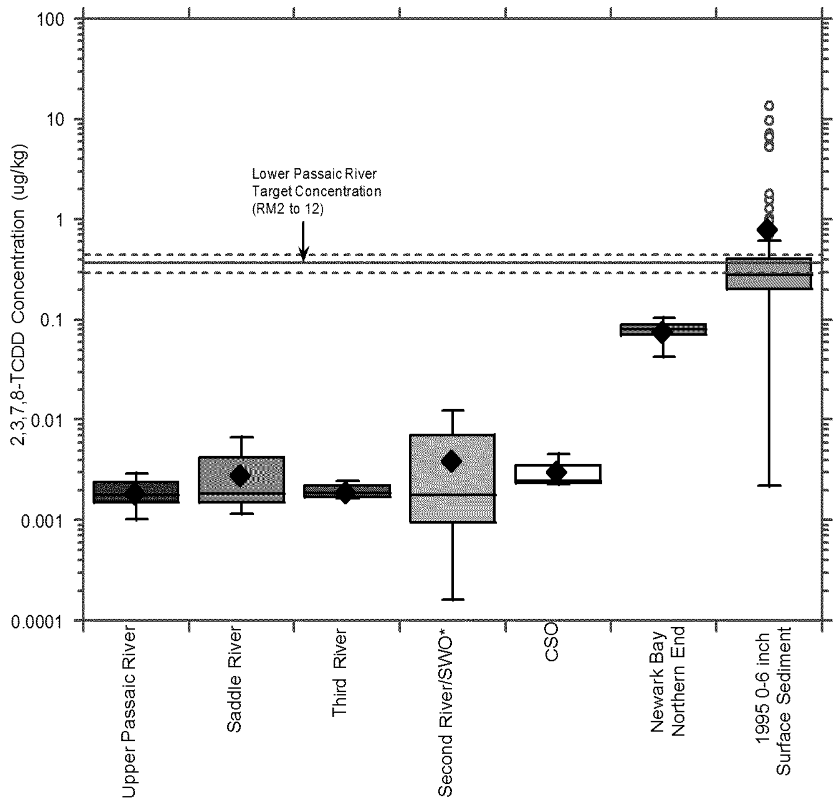
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Solids
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-2

2014

Source Concentration of 2,3,7,8-TCDD



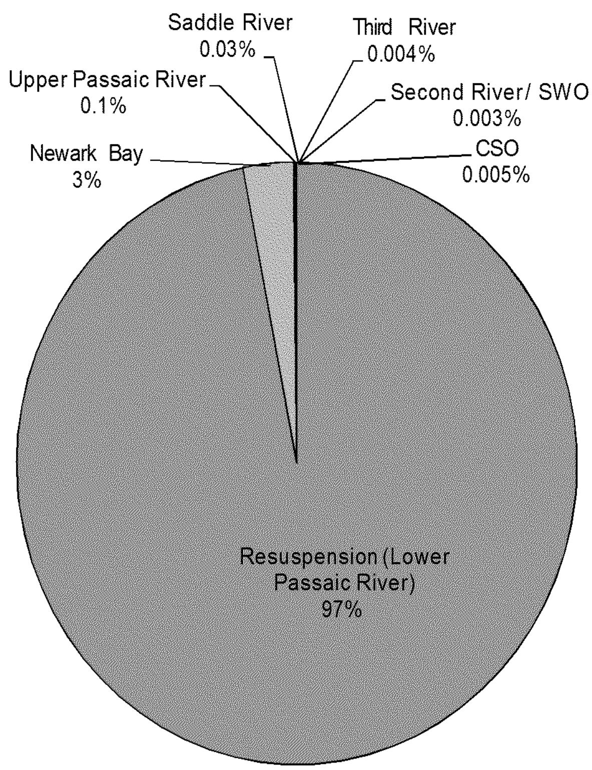
Legend

- Maximum
- 75% quartile
- Median
- 25% quartile
- Minimum
- Outliers
- Mean ± 2 standard errors
- ◆ Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

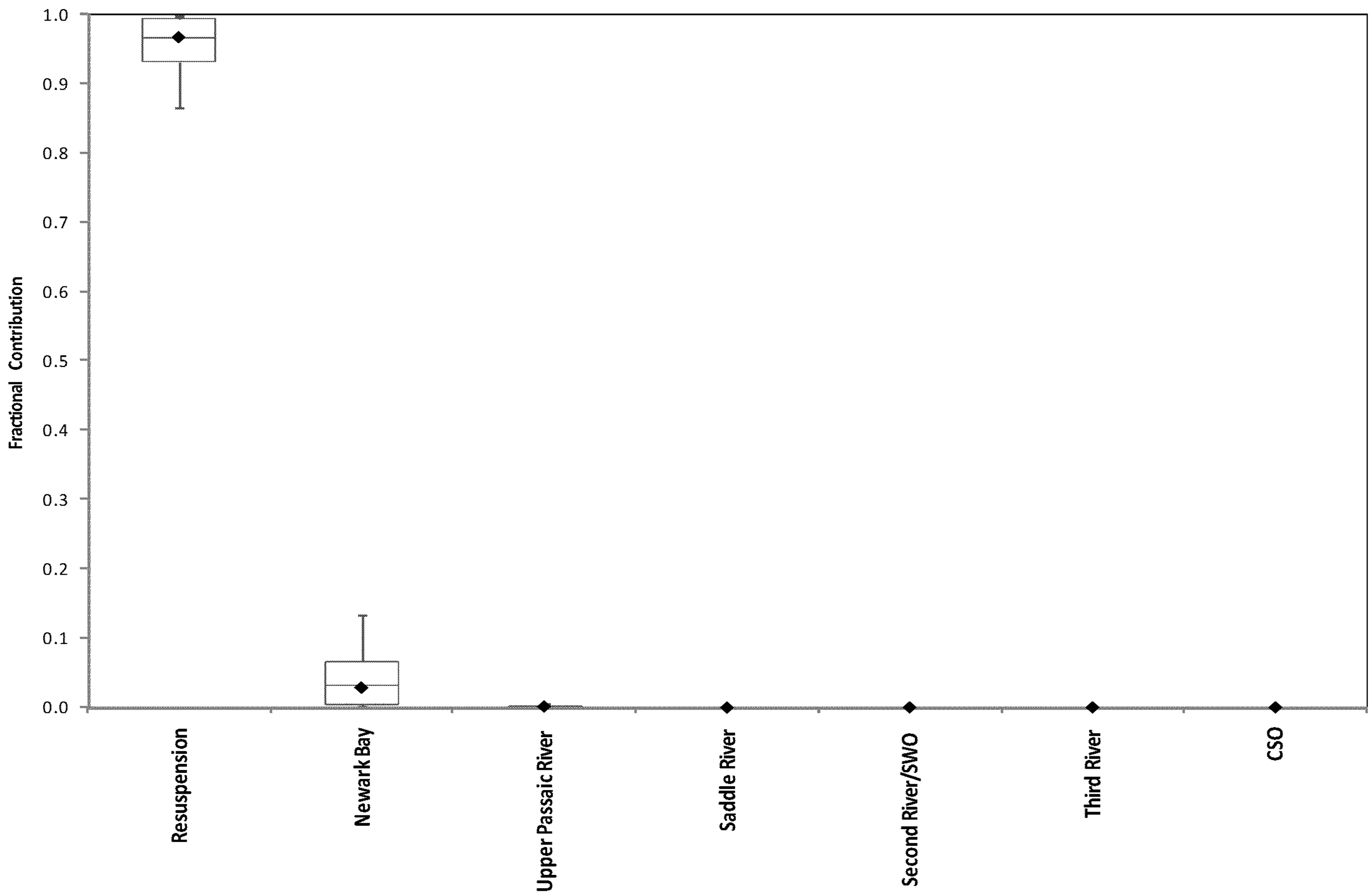
Best Estimate Mass Balance for 2,3,7,8-TCDD



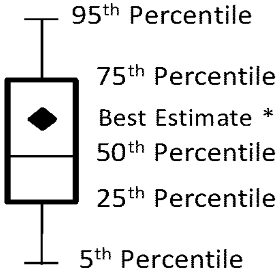
Legend

- Upper Passaic River
- Saddle River
- Second River/SWO
- Third River
- CSO
- Newark Bay Northern End
- Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for 2,3,7,8-TCDD *Lower Eight Miles of the Lower Passaic River*	Figure 4-3a 2014



Legend



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

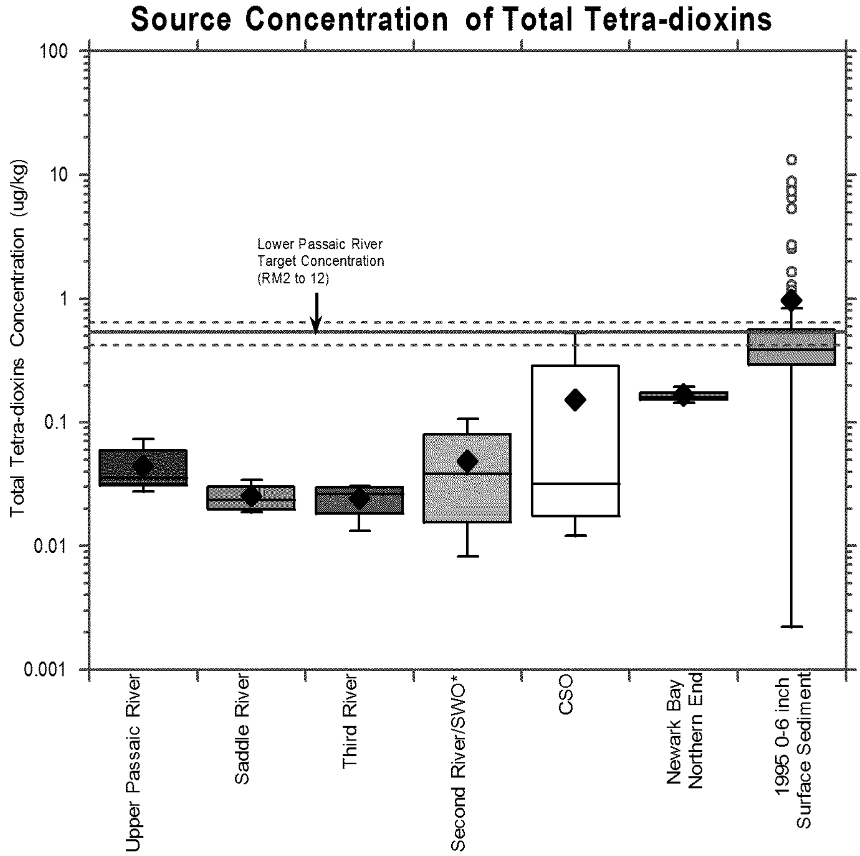
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for 2,3,7,8-TCDD
(Results from Monte Carlo Analysis and Best Estimate Solution)

Lower Eight Miles of the Lower Passaic River

Figure 4-3b

2014



Legend

Maximum

75% quartile

Median

25% quartile

Minimum

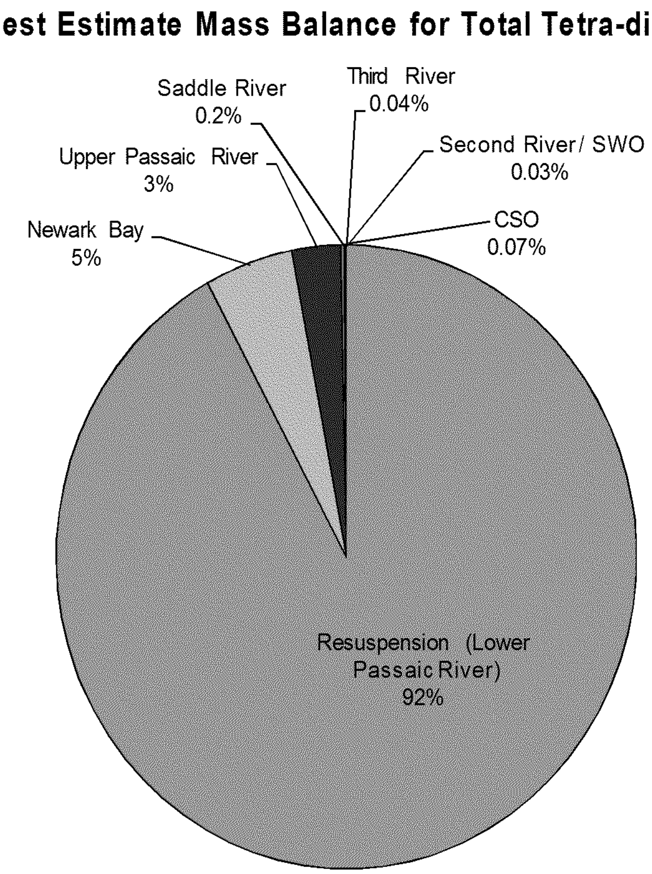
Outliers

Mean ± 2 standard errors

Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)



Legend

Upper Passaic River

Saddle River

Second River/SWO

Third River

CSO

Newark Bay Northern End

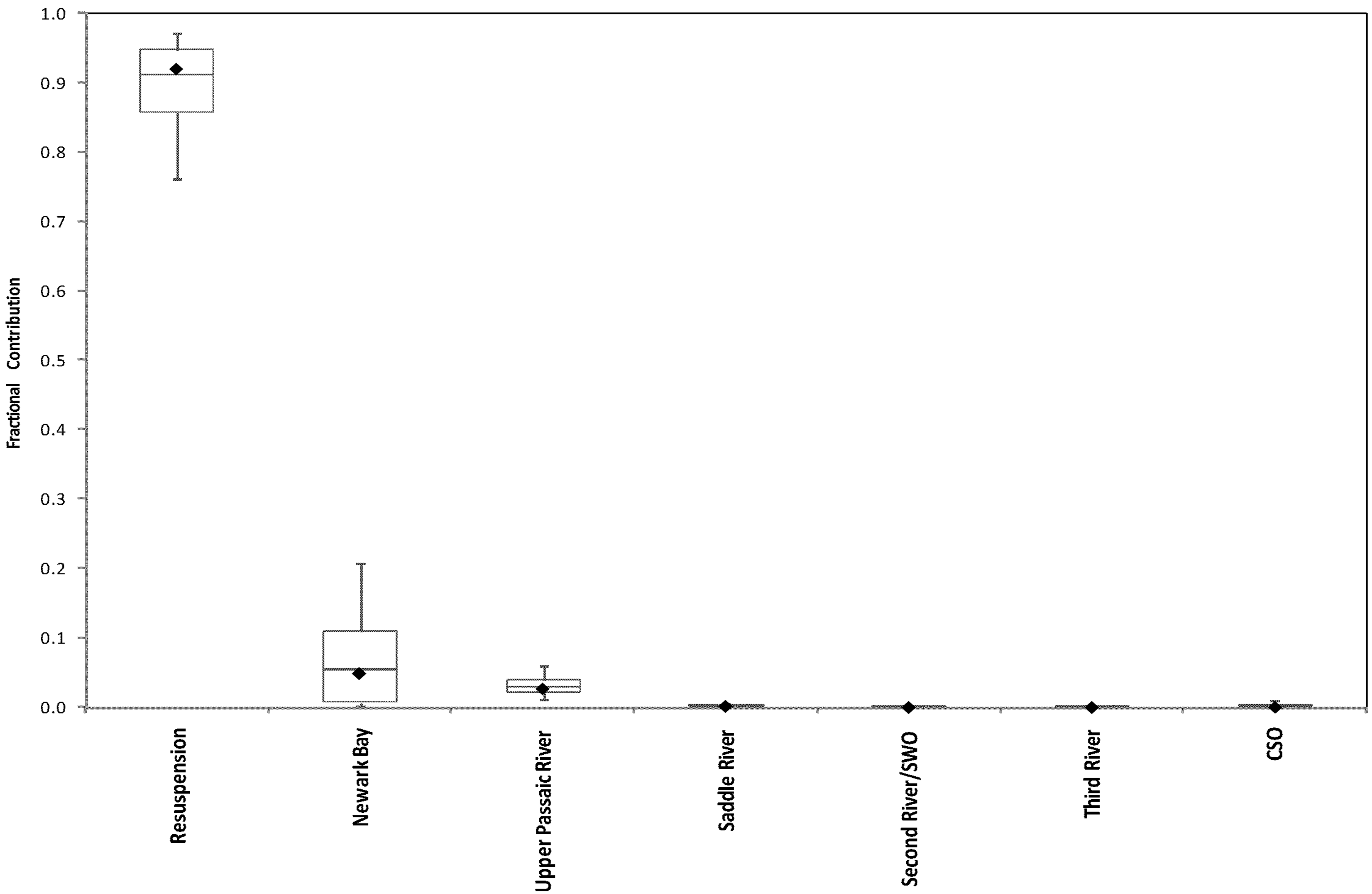
Resuspension (Lower Passaic River)

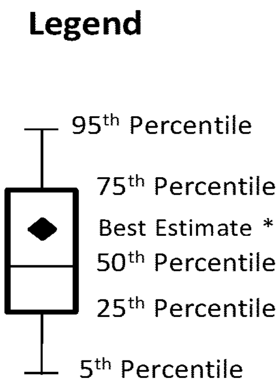
Source Concentration and Mass Balance for Total Tetra-dioxins

Lower Eight Miles of the Lower Passaic River

Figure 4-4a

2014





Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

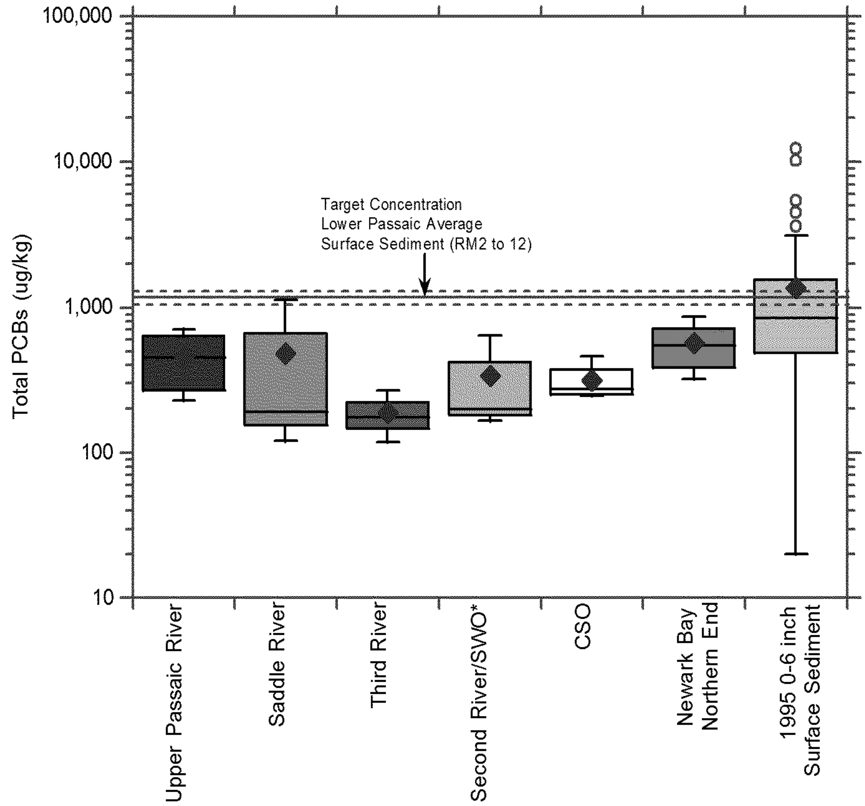
Fractional Contribution for Total Tetra-Dioxins
(Results from Monte Carlo Analysis and Best Estimate Solution)

Lower Eight Miles of the Lower Passaic River

Figure 4-4b

2014

Source Concentration of Total PCBs



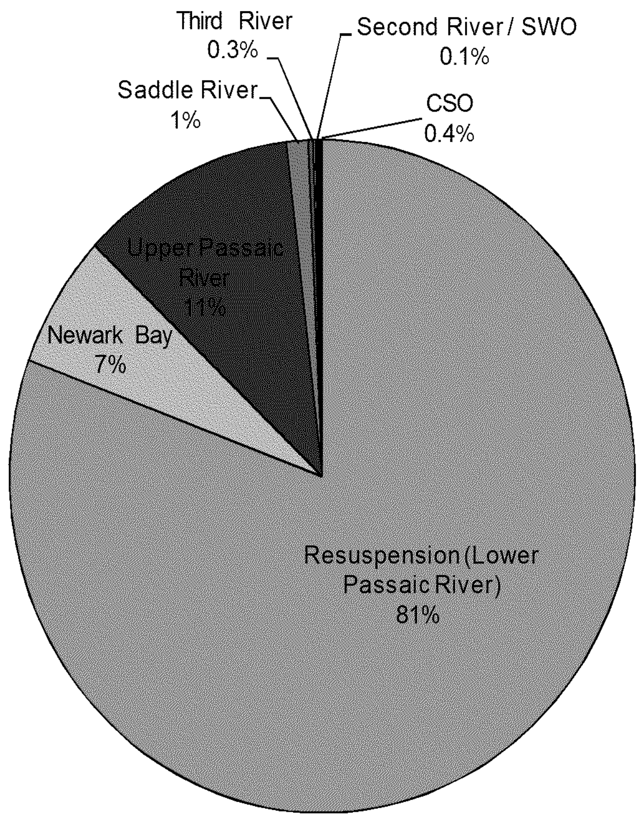
Legend

Maximum
75% quartile
Median
25% quartile
Minimum
Outliers
Mean ± 2 standard errors
Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

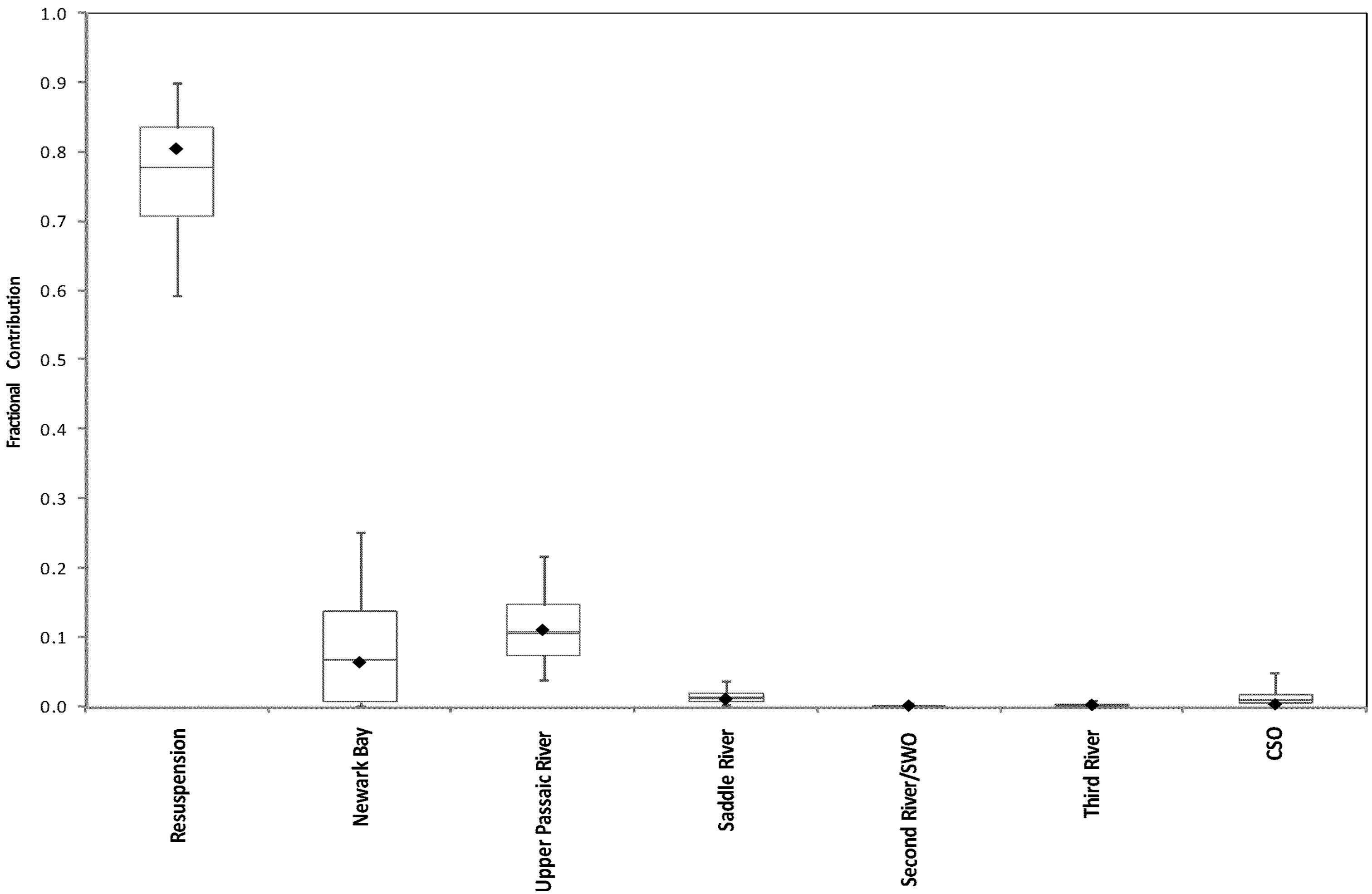
Best Estimate Mass Balance for Total PCBs



Legend

- Upper Passaic River
- Saddle River
- Second River/SWO
- Third River
- CSO
- Newark Bay Northern End
- Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for Total PCBs *Lower Eight Miles of the Lower Passaic River*	Figure 4-5a 2014



Legend

95th Percentile
75th Percentile
Best Estimate *
50th Percentile
25th Percentile
5th Percentile

Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

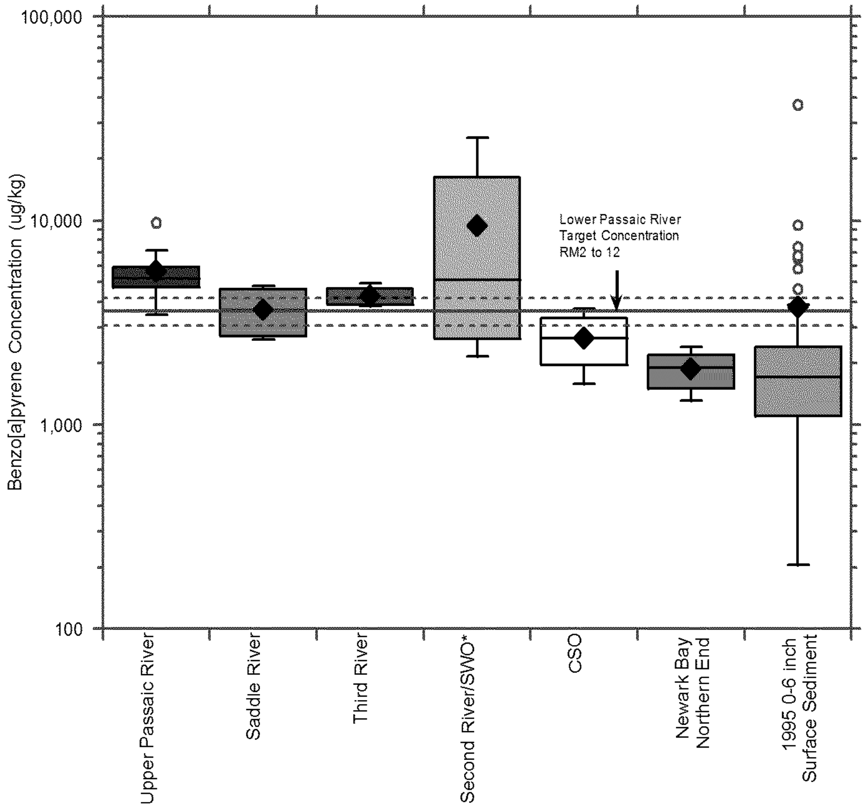
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Total PCBs
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

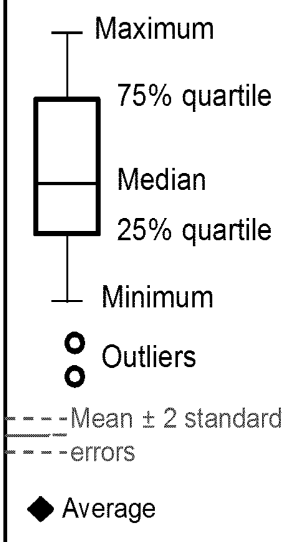
Figure 4-5b

2014

Source Concentration of Benzo[a]pyrene



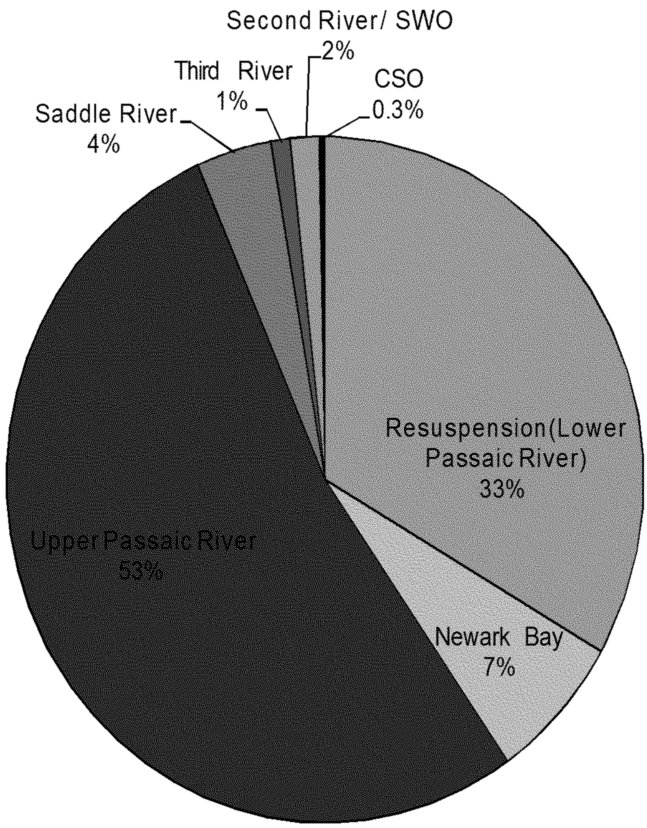
Legend



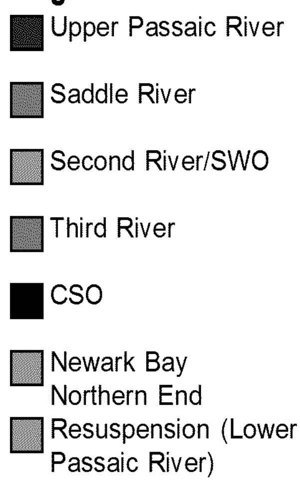
Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

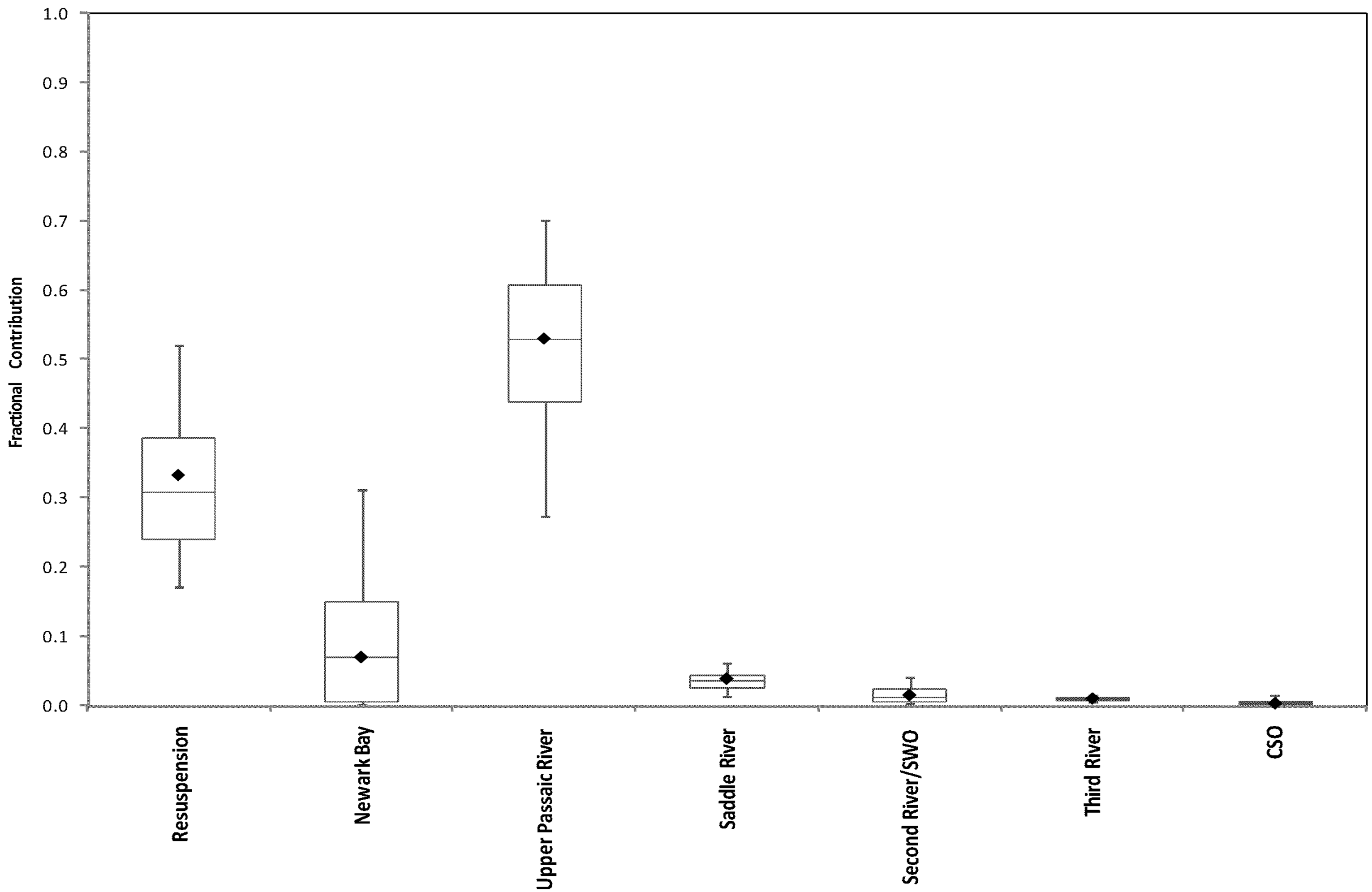
Best Estimate Mass Balance for Benzo[a]pyrene

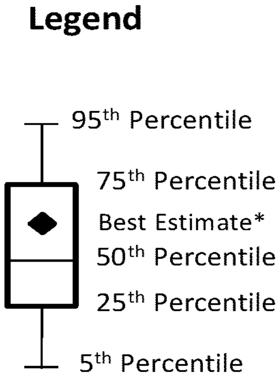


Legend



	Source Concentration and Mass Balance for Benzo[a]pyrene *Lower Eight Miles of the Lower Passaic River*	Figure 4-6a 2014





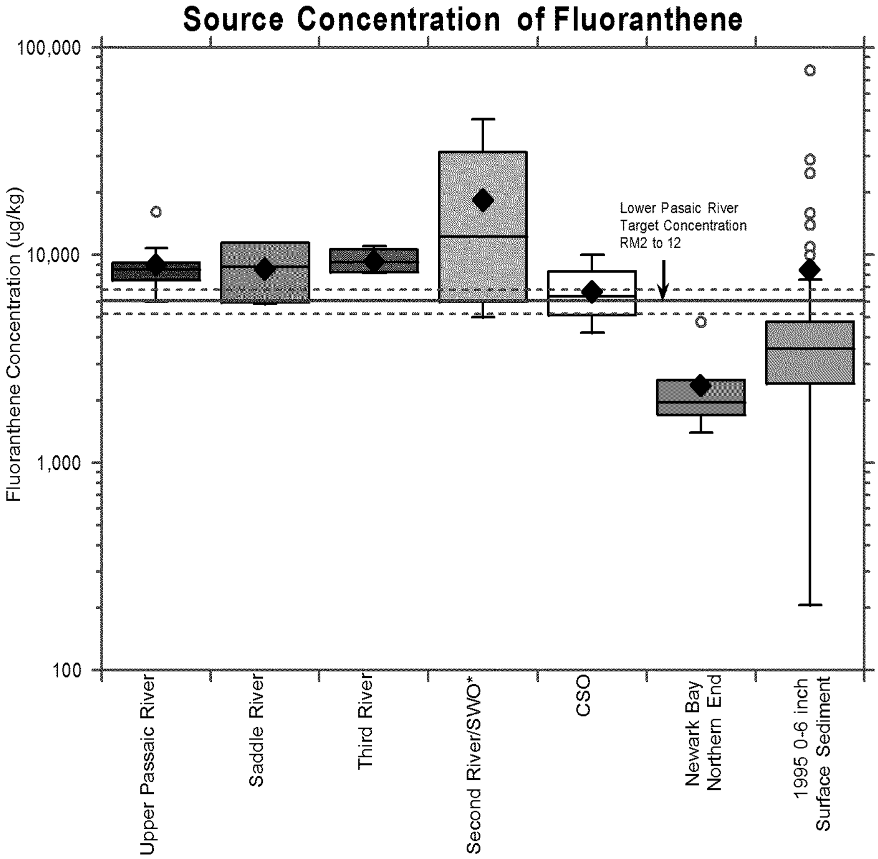
Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Benzo[a]pyrene
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-6b

2014



Legend

Maximum

75% quartile

Median

25% quartile

Minimum

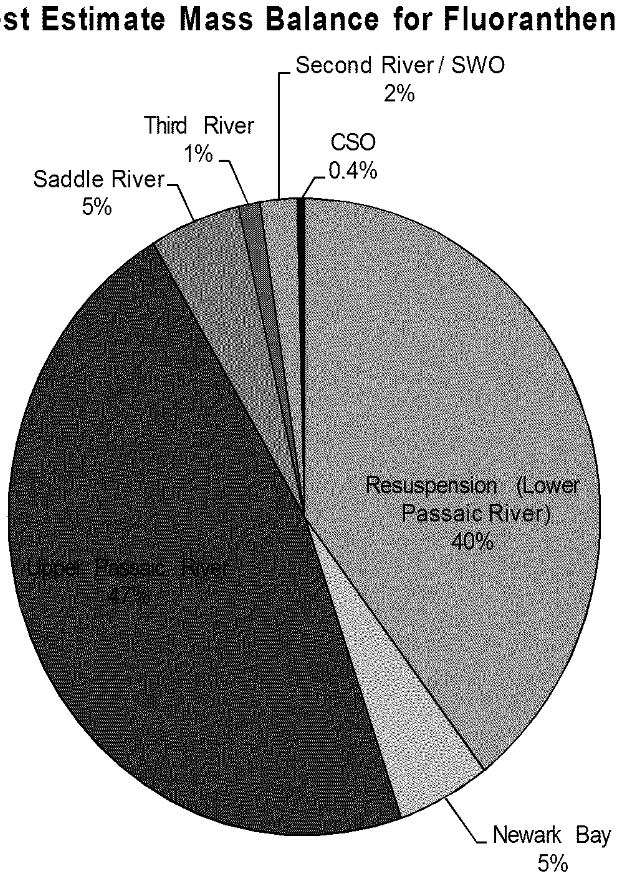
Outliers

Mean ± 2 standard errors

Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)



Legend

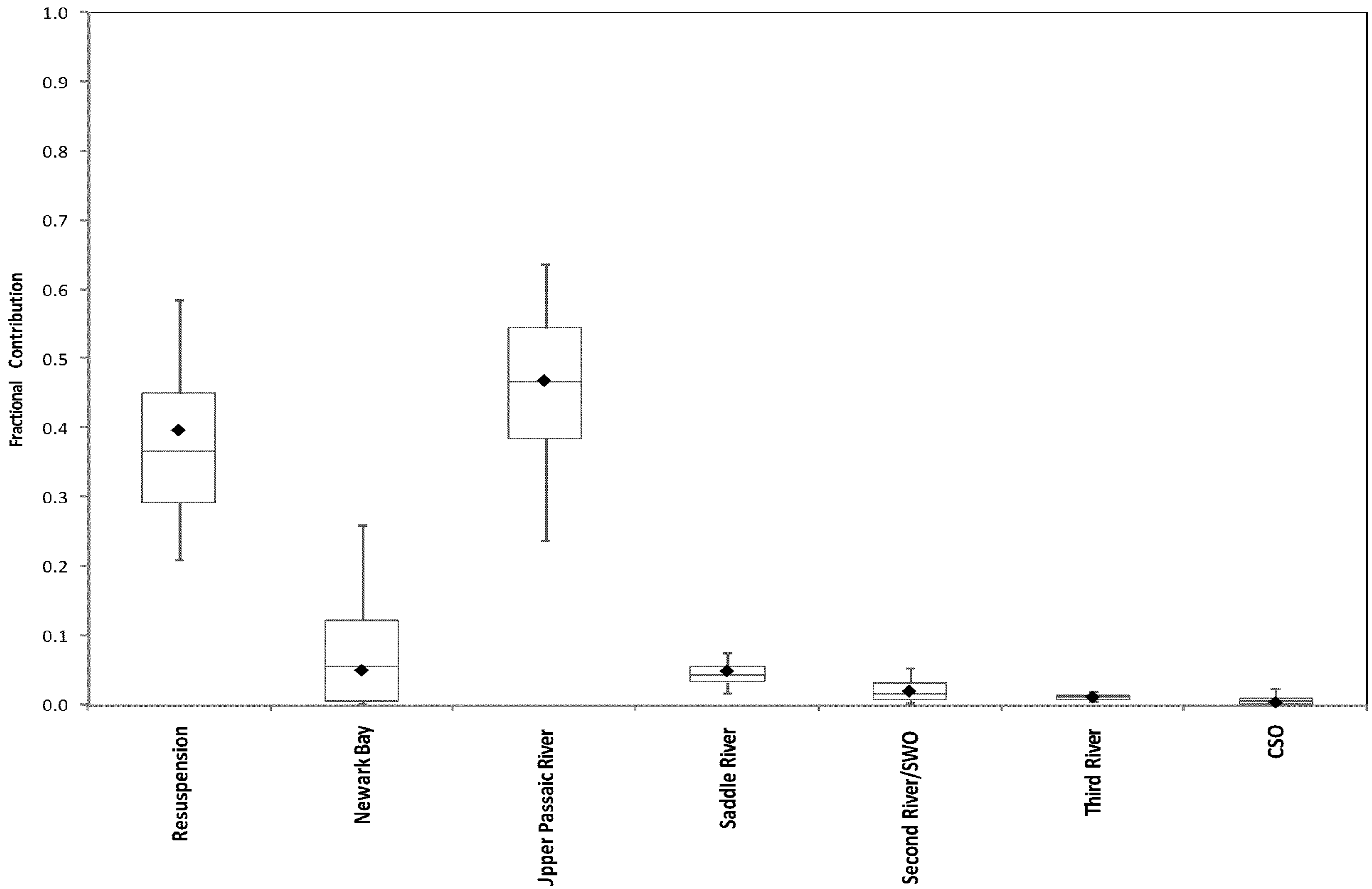
- Upper Passaic River
- Saddle River
- Second River/SWO
- Third River
- CSO
- Newark Bay Northern End
- Resuspension (Lower Passaic River)

Source Concentration and Mass Balance for Fluoranthene

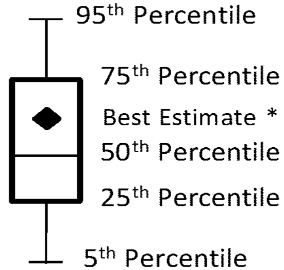
Lower Eight Miles of the Lower Passaic River

Figure 4-7a

2014



Legend



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

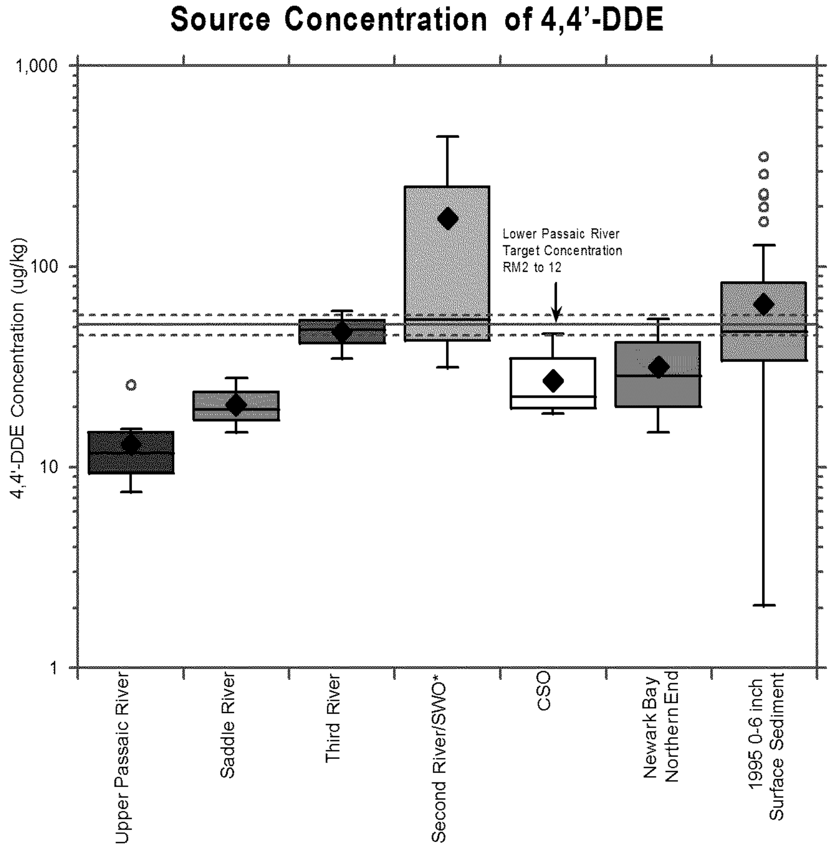
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Fluoranthene
(Results from Monte Carlo Analysis and Best Estimate Solution)

Lower Eight Miles of the Lower Passaic River

Figure 4-7b

2014



Legend

Maximum

75% quartile

Median

25% quartile

Minimum

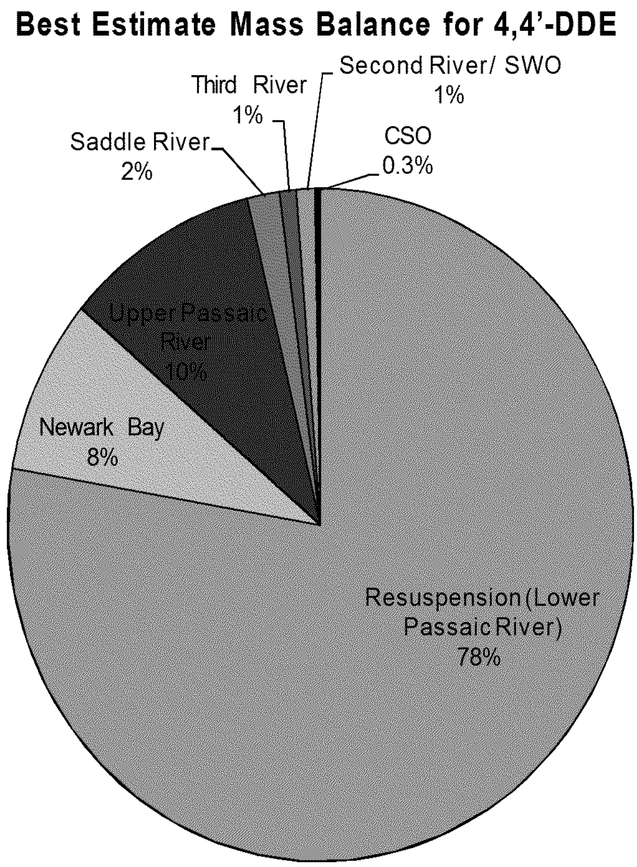
Outliers

Mean ± 2 standard errors

Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)



Legend

Upper Passaic River

Saddle River

Second River/SWO

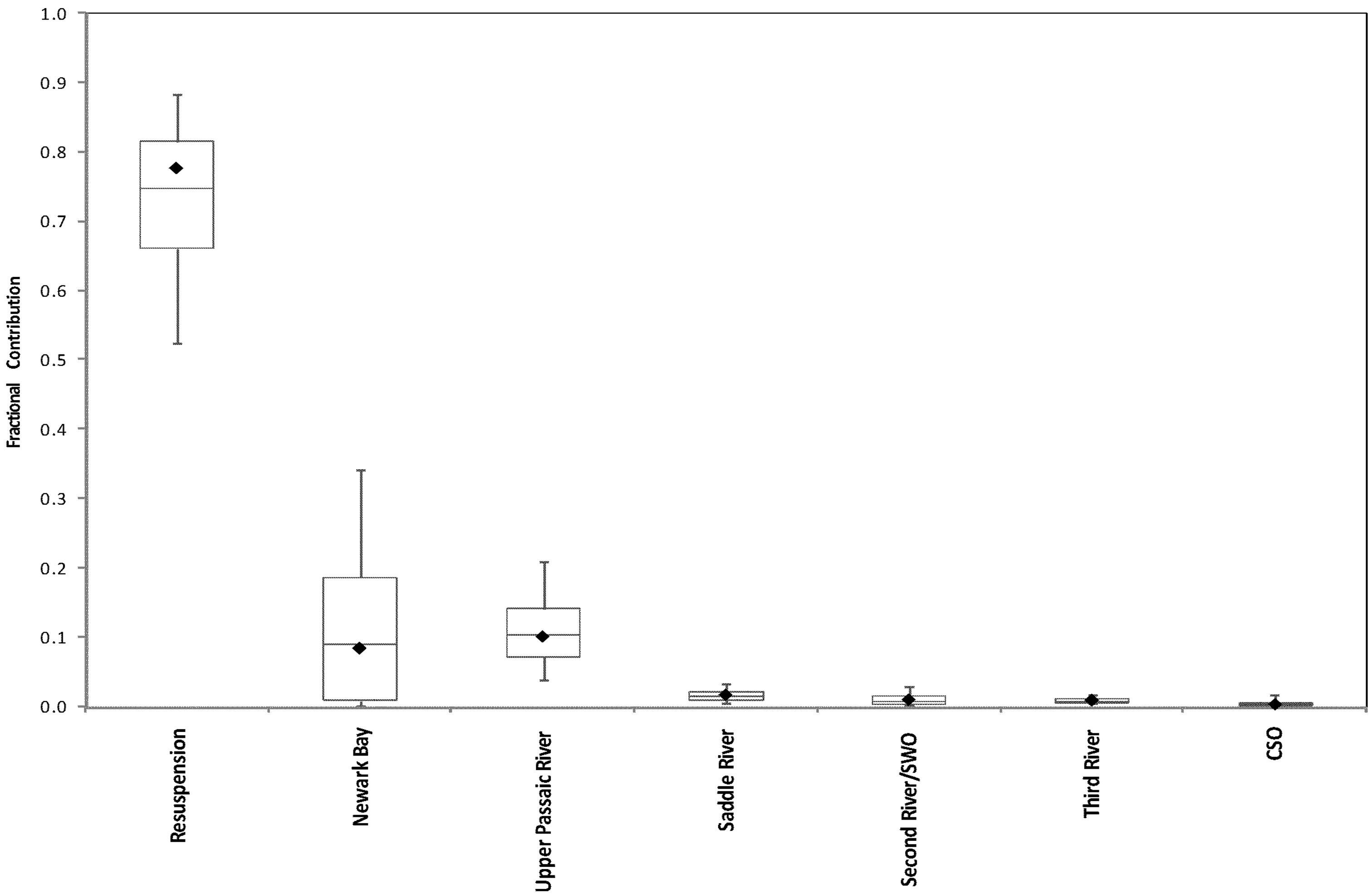
Third River

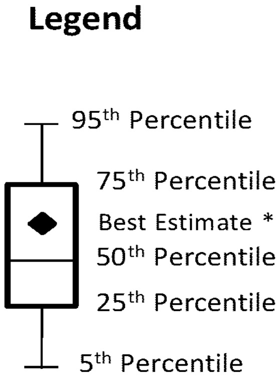
CSO

Newark Bay Northern End

Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for 4,4'-DDE *Lower Eight Miles of the Lower Passaic River*	Figure 4-8a 2014





Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

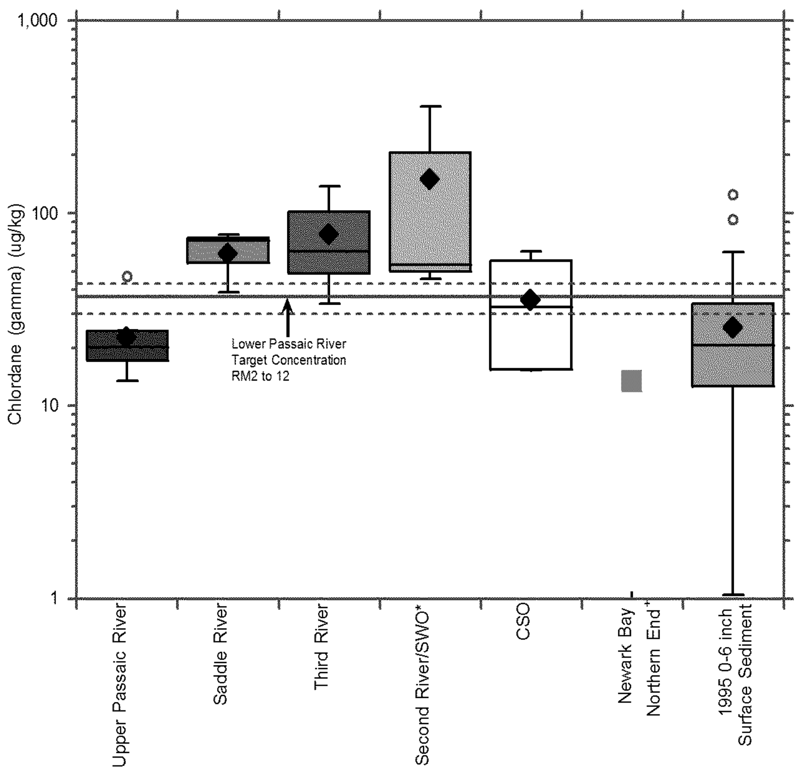
Fractional Contribution for 4,4'-DDE
(Results from Monte Carlo Analysis and Best Estimate Solution)

Lower Eight Miles of the Lower Passaic River

Figure 4-8b

2014

Source Concentration of gamma-Chlordane



Legend

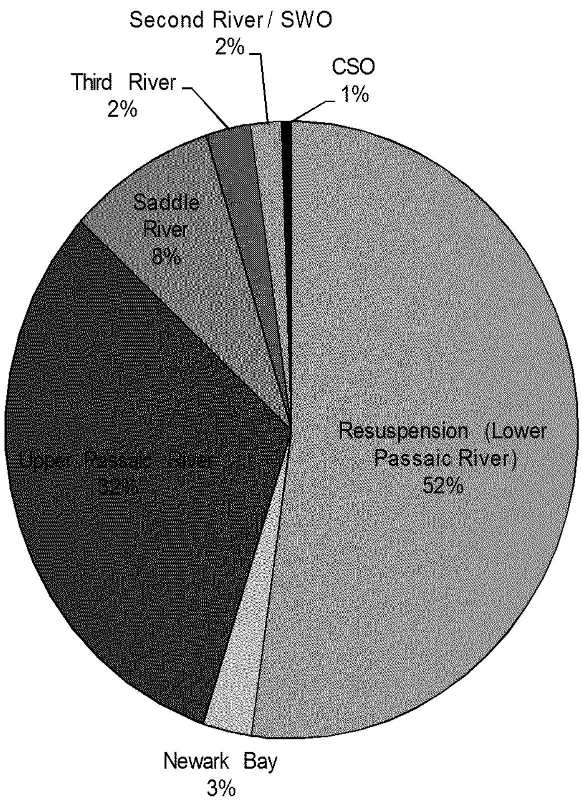
- Maximum
- 75% quartile
- Median
- 25% quartile
- Minimum
- Outliers
- Mean ± 2 standard errors
- Average

Notes

*Second River Results are used to represent the SWOs. (see Appendix F)

+Robinson (2002)

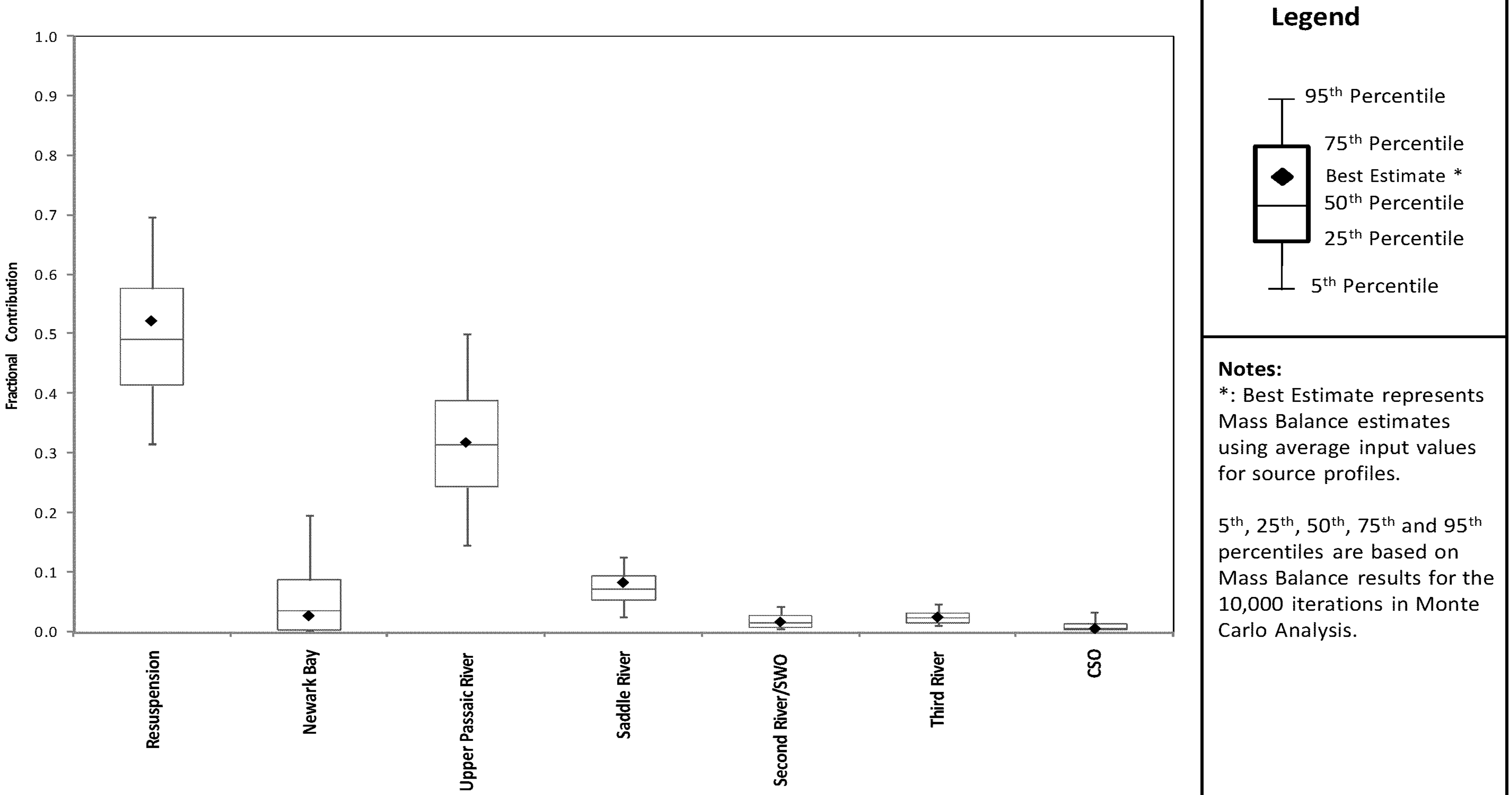
Best Estimate Mass Balance for gamma-Chlordane



Legend

- Upper Passaic River
- Saddle River
- Second River/SWO
- Third River
- CSO
- Newark Bay Northern End
- Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for gamma-Chlordane *Lower Eight Miles of the Lower Passaic River*	Figure 4-9a 2014



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

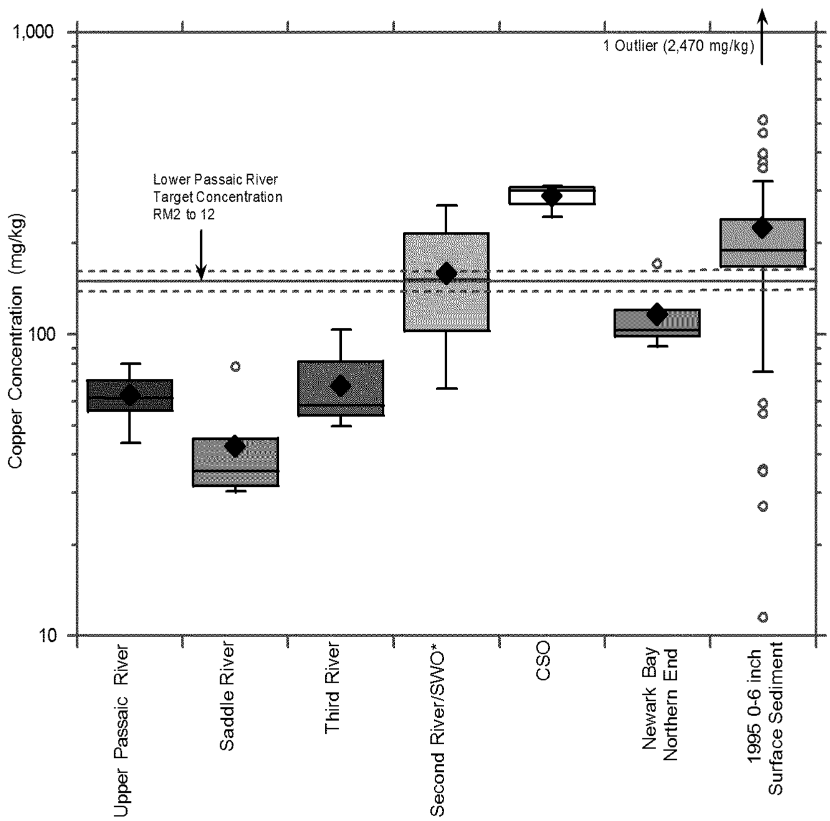
Fractional Contribution for gamma-Chlordane
(Results from Monte Carlo Analysis and Best Estimate Solution)

Lower Eight Miles of the Lower Passaic River

Figure 4-9b

2014

Source Concentration of Copper



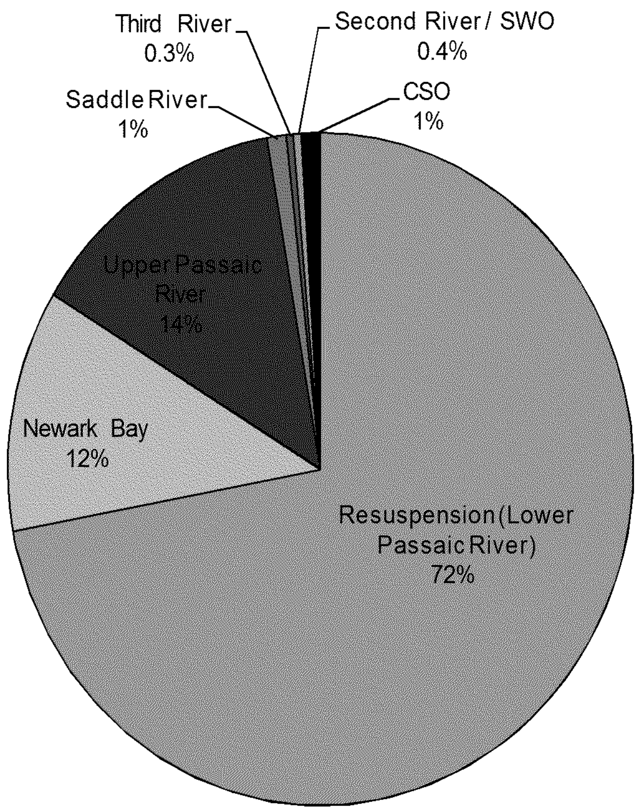
Legend

Maximum
75% quartile
Median
25% quartile
Minimum
Outliers
Mean ± 2 standard errors
Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

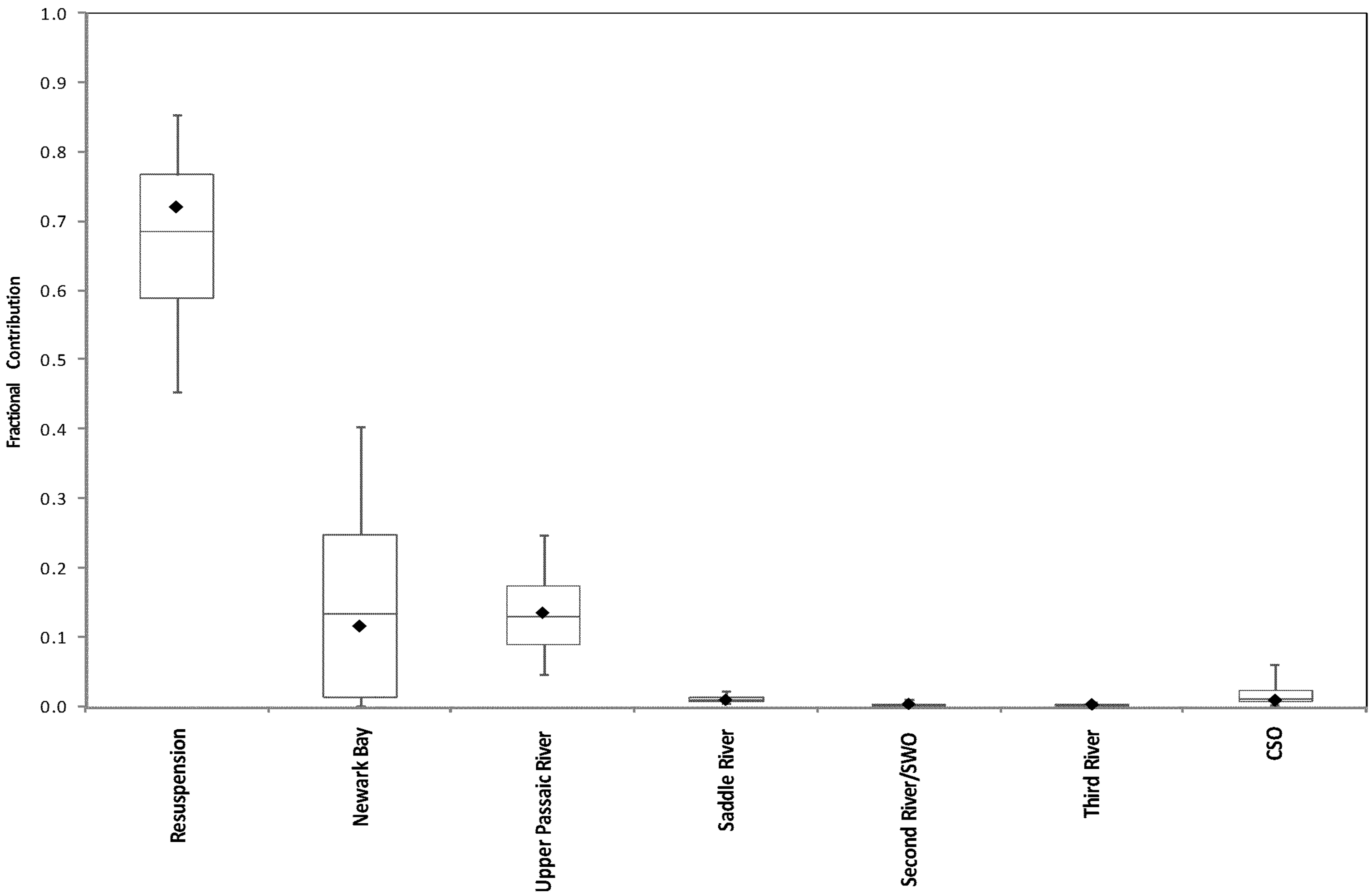
Best Estimate Mass Balance for Copper

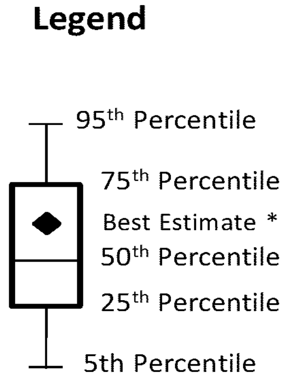


Legend

Upper Passaic River
Saddle River
Second River/SWO
Third River
CSO
Newark Bay Northern End
Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for Copper *Lower Eight Miles of the Lower Passaic River*	Figure 4-10a 2014





Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

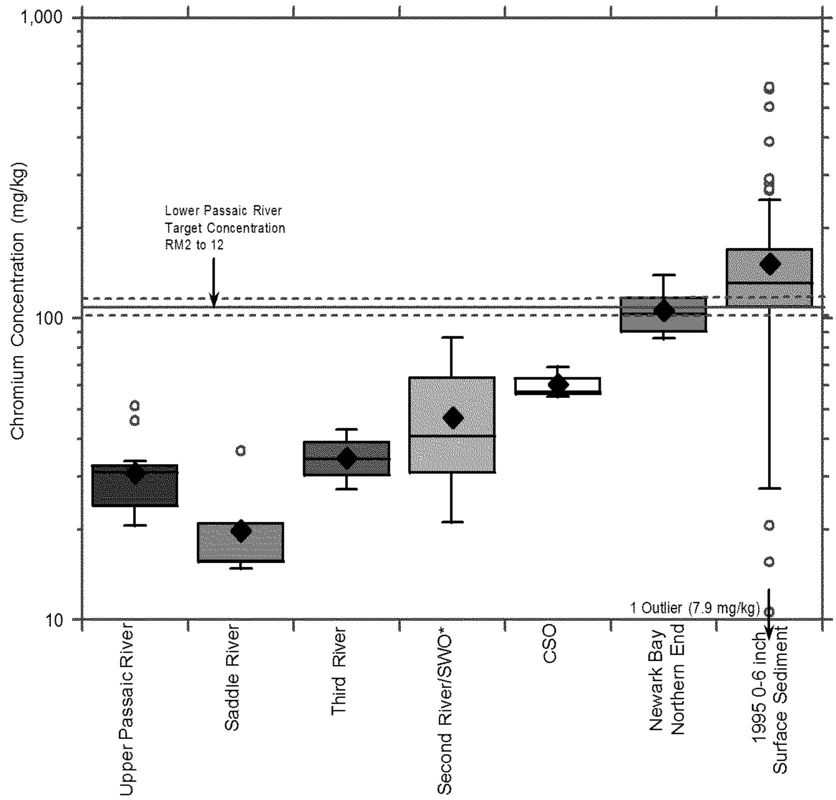
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Copper
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-10b

2014

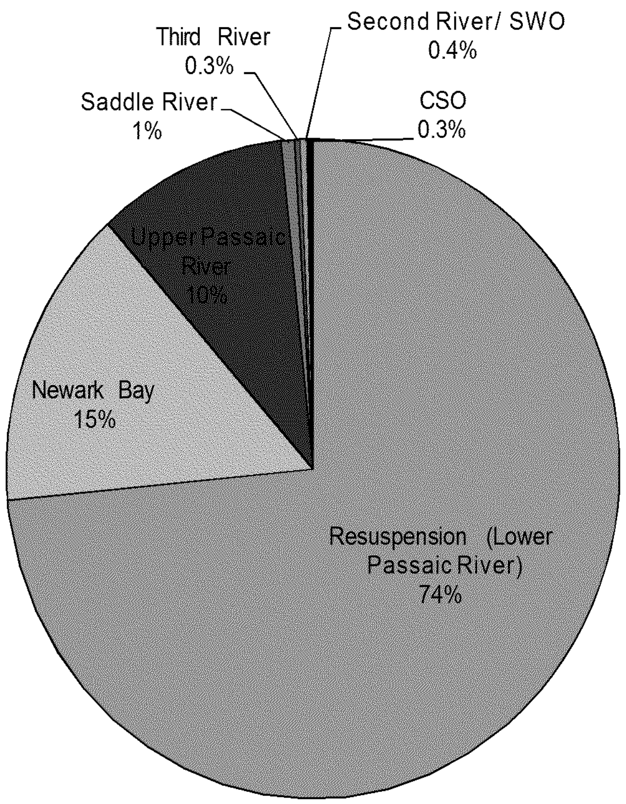
Source Concentration of Chromium



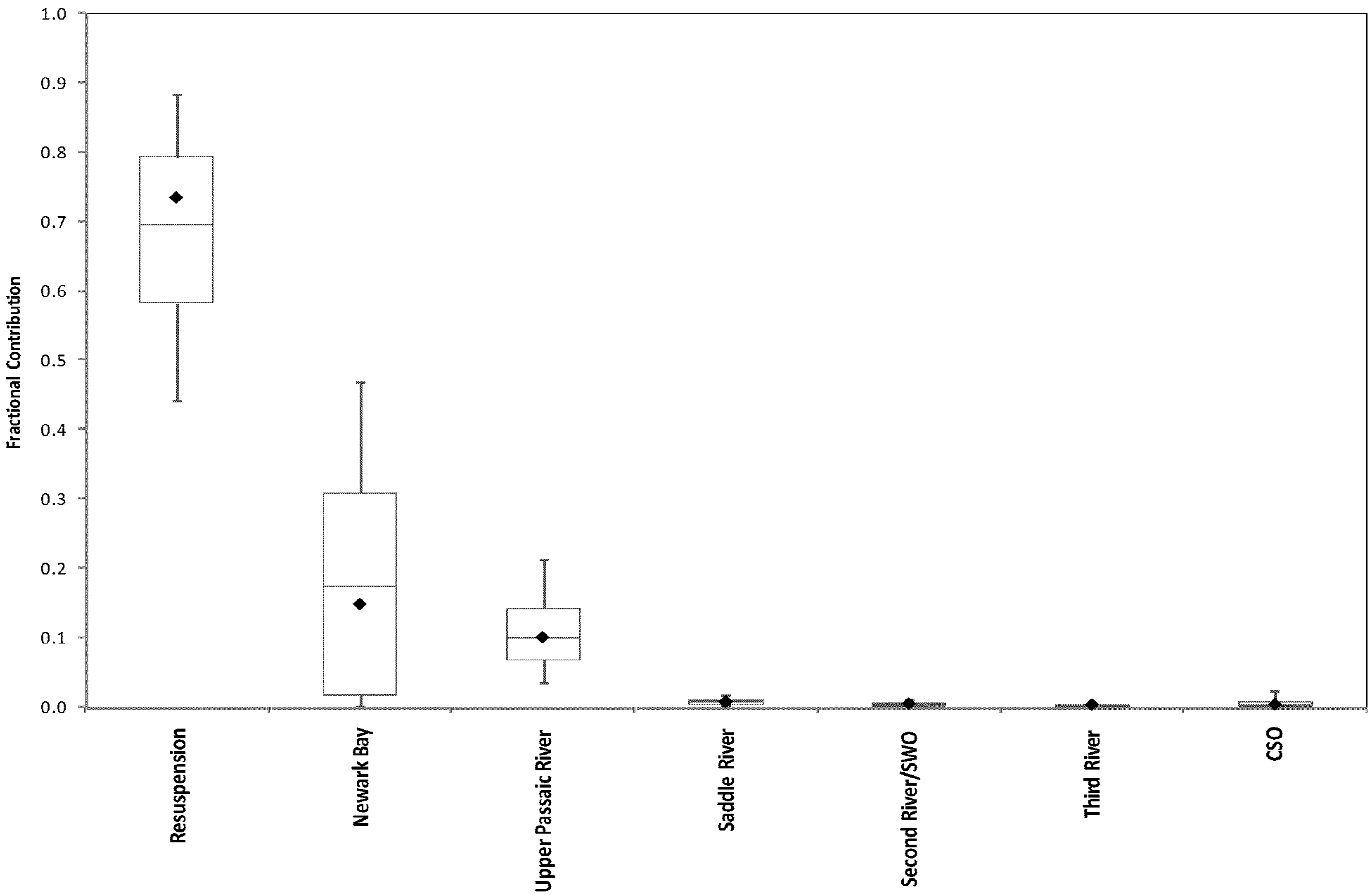
Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

Best Estimate Mass Balance for Chromium



	Source Concentration and Mass Balance for Chromium *Lower Eight Miles of the Lower Passaic River*	Figure 4-11a 2014



Legend

95th Percentile
75th Percentile
Best Estimate*
50th Percentile
25th Percentile
5th Percentile

Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

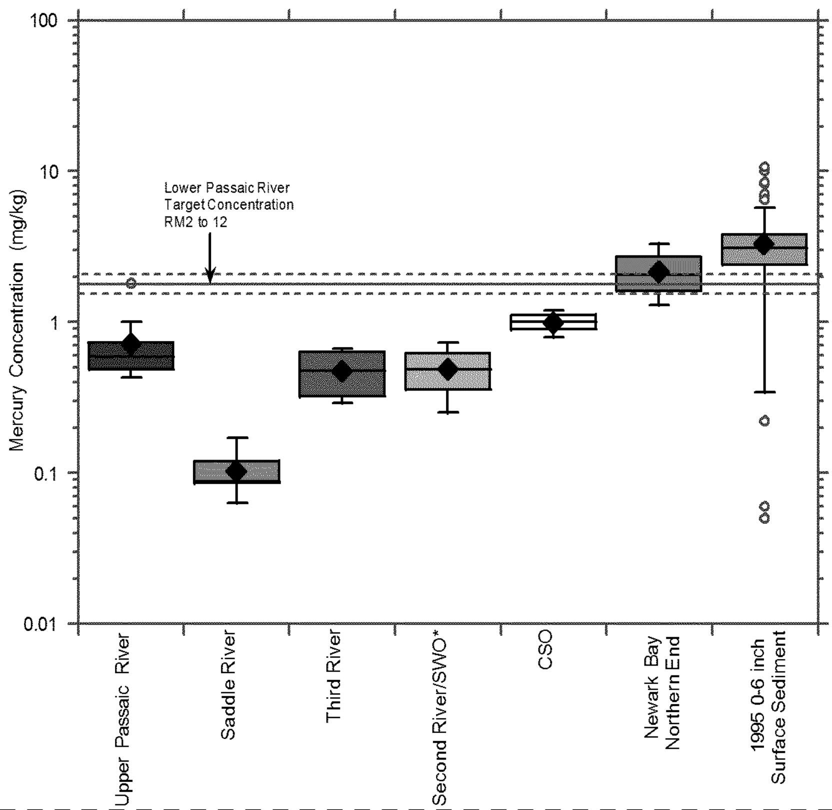
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Chromium
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-11b

2014

Source Concentration of Mercury



Legend

Maximum

75% quartile

Median

25% quartile

Minimum

Outliers

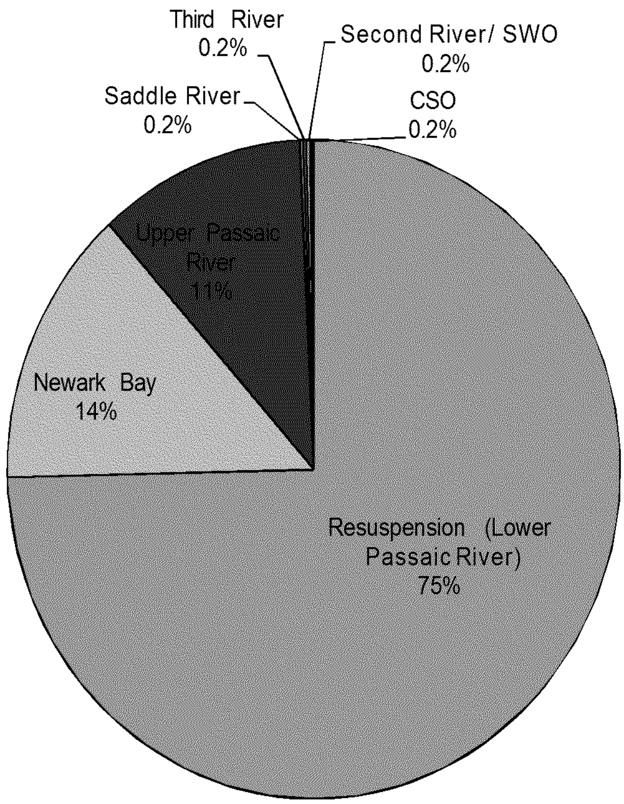
Mean ± 2 standard errors

Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

Best Estimate Mass Balance for Mercury



Legend

Upper Passaic River

Saddle River

Second River/SWO

Third River

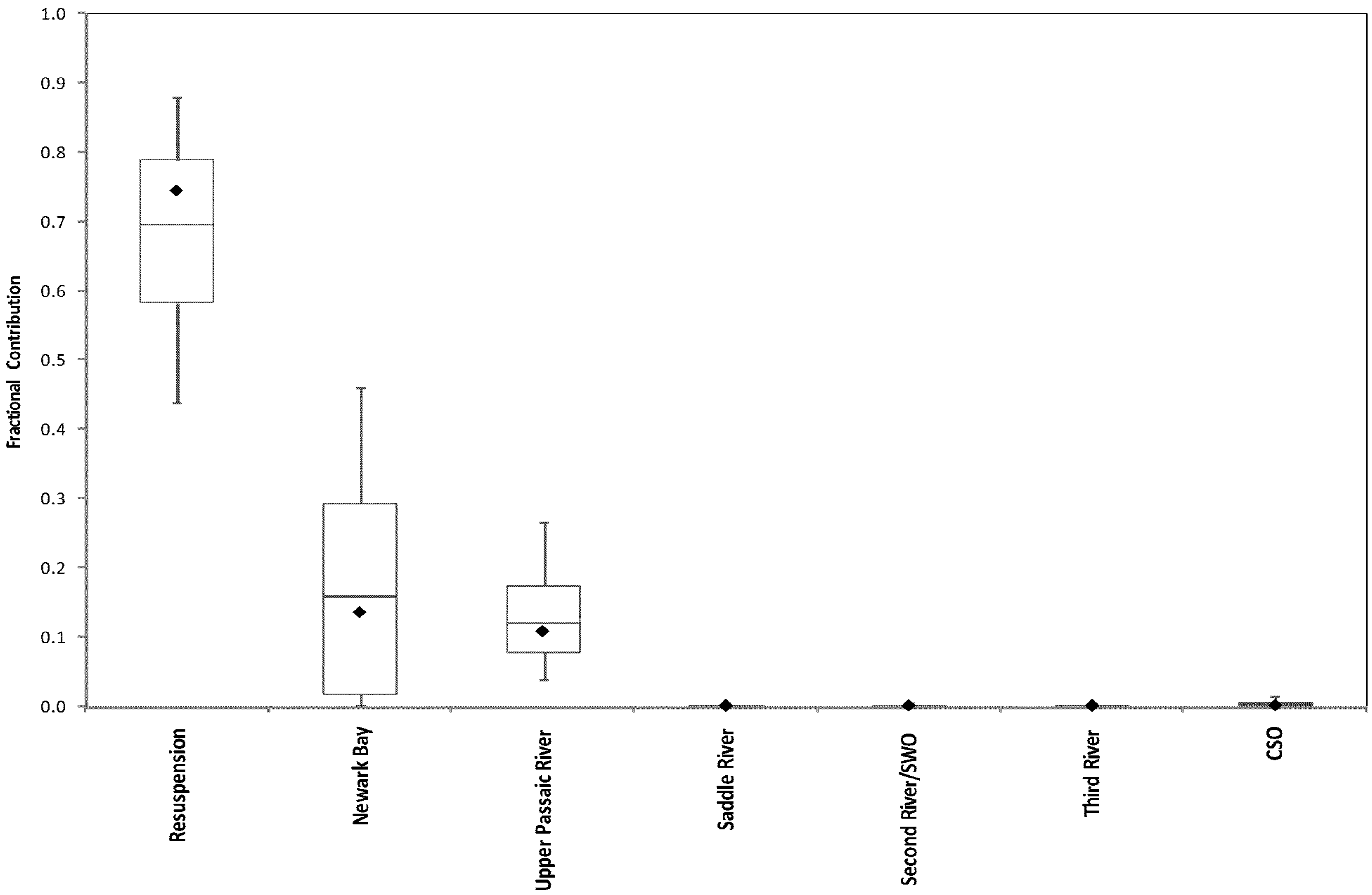
CSO

Newark Bay Northern End

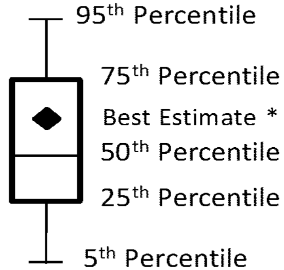
Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for Mercury *Lower Eight Miles of the Lower Passaic River*	Figure 4-12a 2014

FOIA_06018_0000007_0113



Legend



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

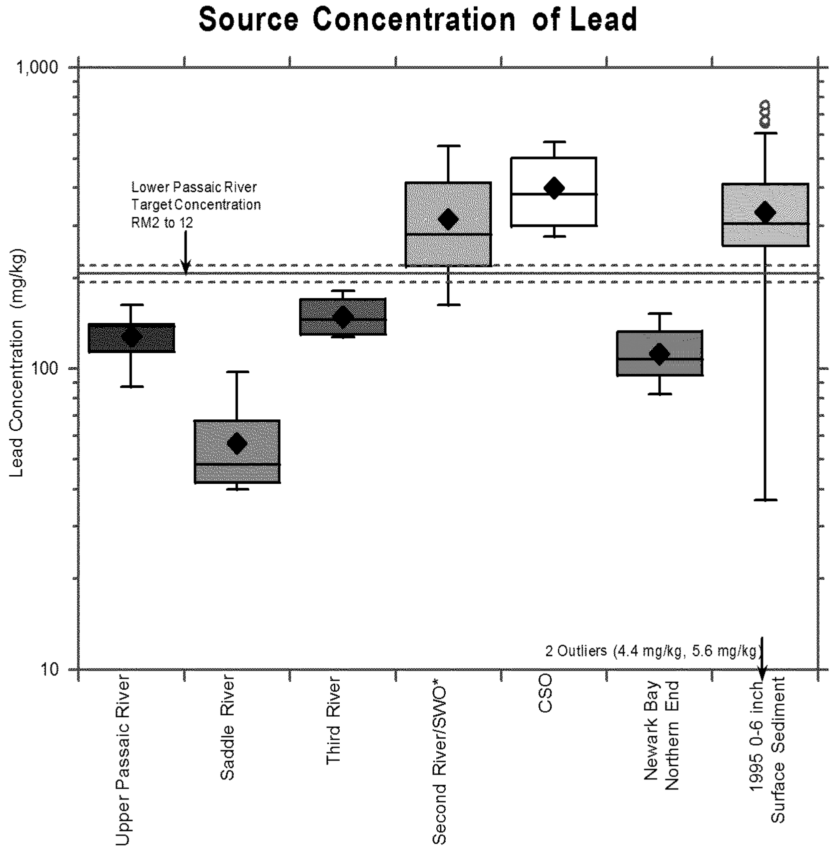
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Mercury
(Results from Monte Carlo Analysis and Best Estimate Solution)

Lower Eight Miles of the Lower Passaic River

Figure 4-12b

2014



Legend

Maximum

75% quartile

Median

25% quartile

Minimum

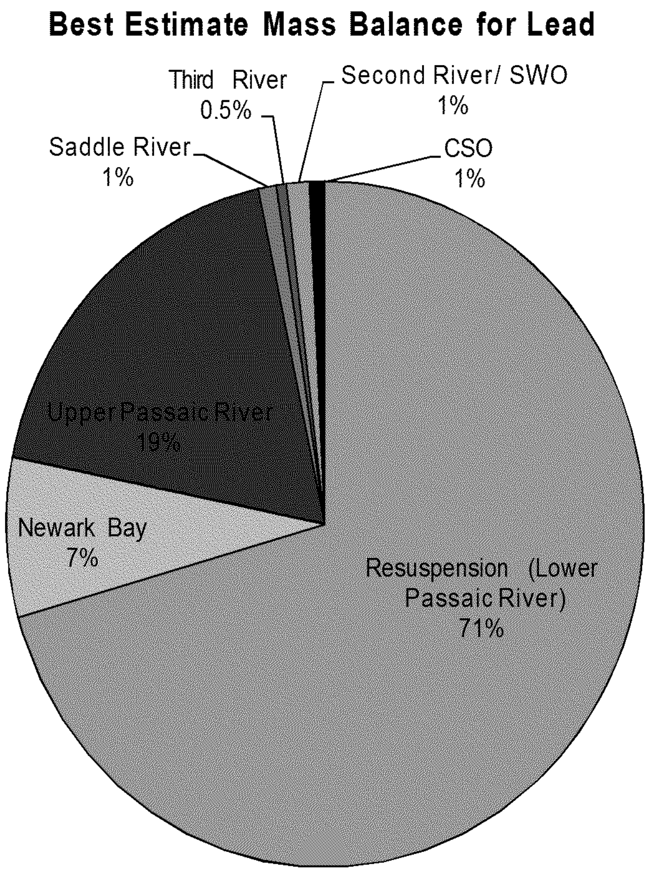
Outliers

Mean ± 2 standard errors

Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)



Legend

Upper Passaic River

Saddle River

Second River/SWO

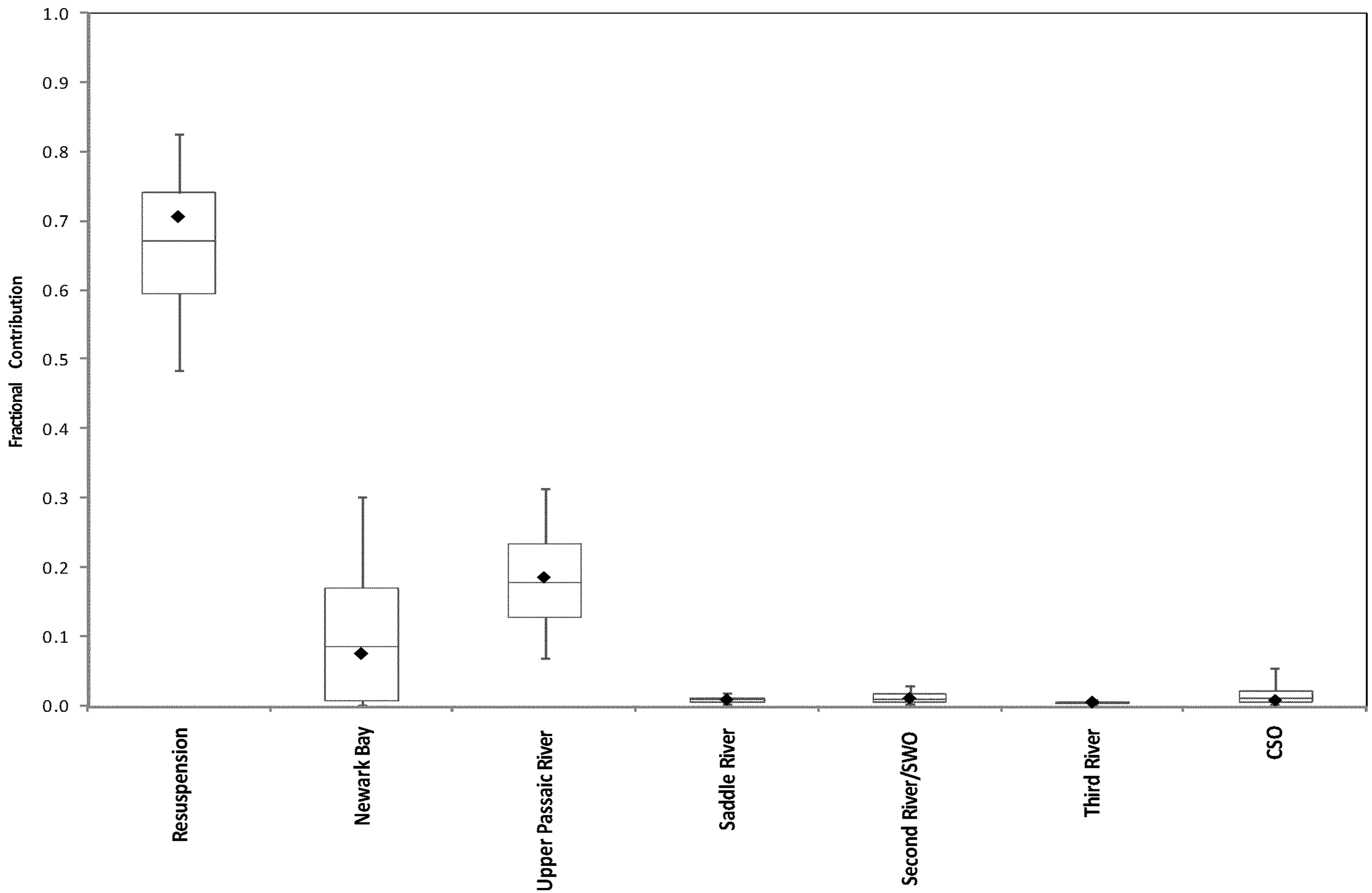
Third River

CSO

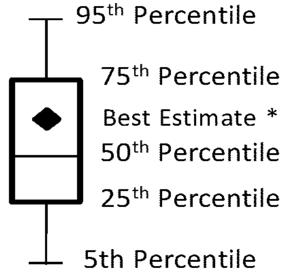
Newark Bay Northern End

Resuspension (Lower Passaic River)

	Source Concentration and Mass Balance for Lead *Lower Eight Miles of the Lower Passaic River*	Figure 4-13a 2014



Legend



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

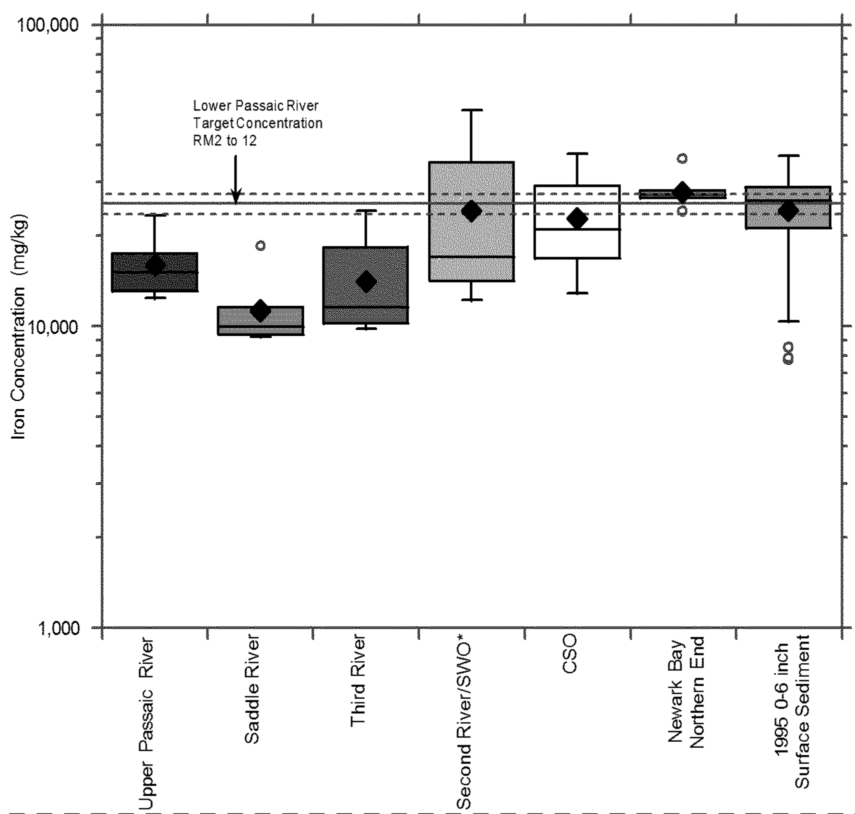
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Lead
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-13b

2014

Source Concentration of Iron



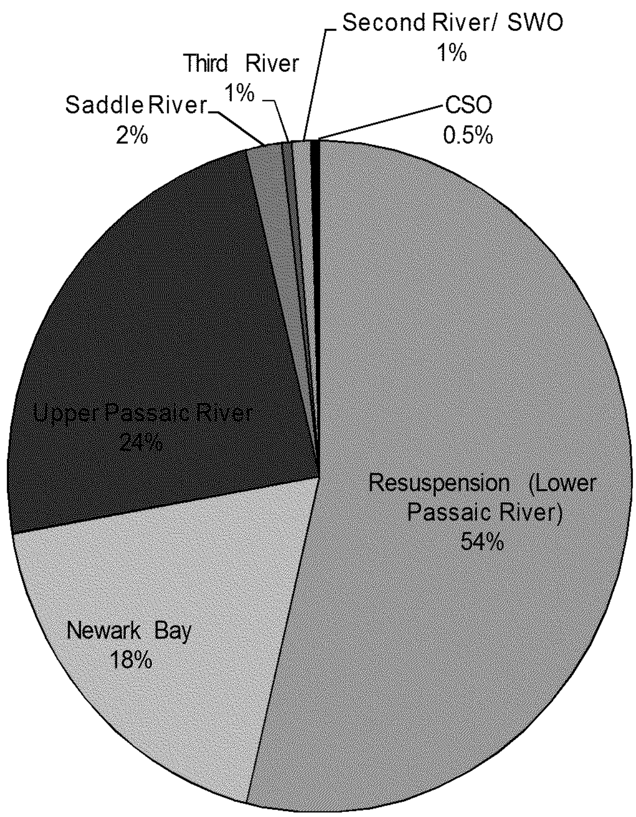
Legend

- Maximum
- 75% quartile
- Median
- 25% quartile
- Minimum
- Outliers
- Mean ± 2 standard errors
- ◆ Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

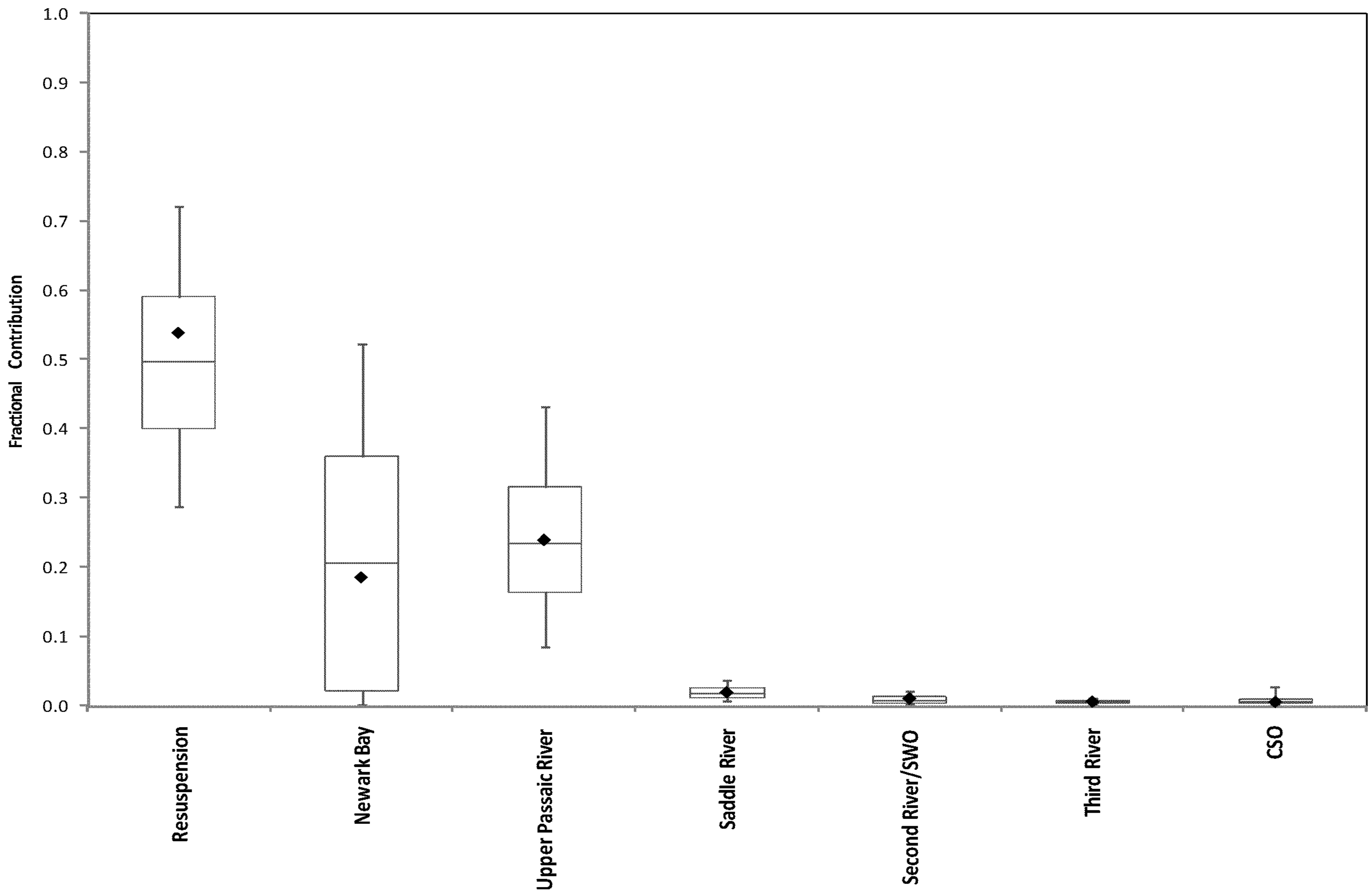
Best Estimate Mass Balance for Iron



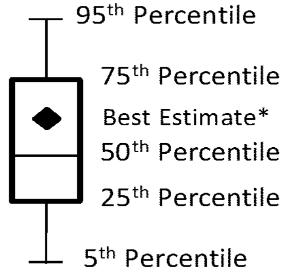
Legend

- Upper Passaic River
- Saddle River
- Second River/SWO
- Third River
- CSO
- Newark Bay Northern End
- Resuspension (Lower Passaic River)

Source Concentration and Mass Balance for Iron *Lower Eight Miles of the Lower Passaic River*	Figure 4-14a 2014



Legend



Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

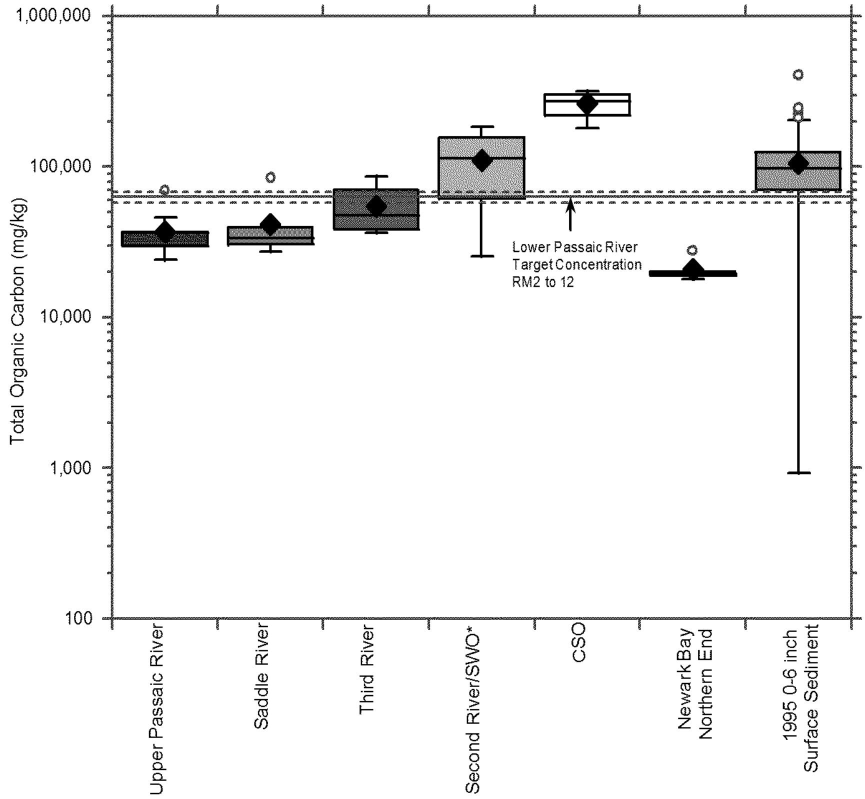
5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Iron
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-14b

2014

Source Concentration of Total Organic Carbon



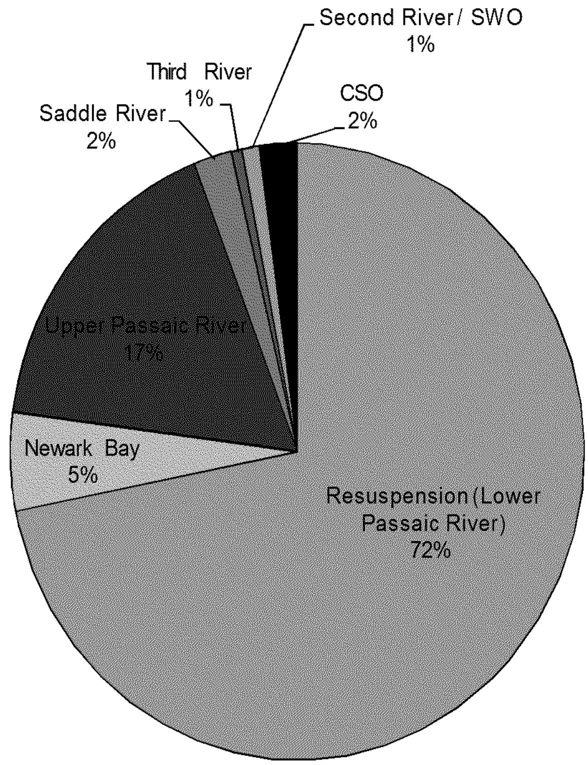
Legend

- Maximum
- 75% quartile
- Median
- 25% quartile
- Minimum
- Outliers
- Mean ± 2 standard errors
- Average

Notes

*: Second River Results are used to represent the SWOs. (see Appendix F)

Best Estimate Mass Balance for Total Organic Carbon



Legend

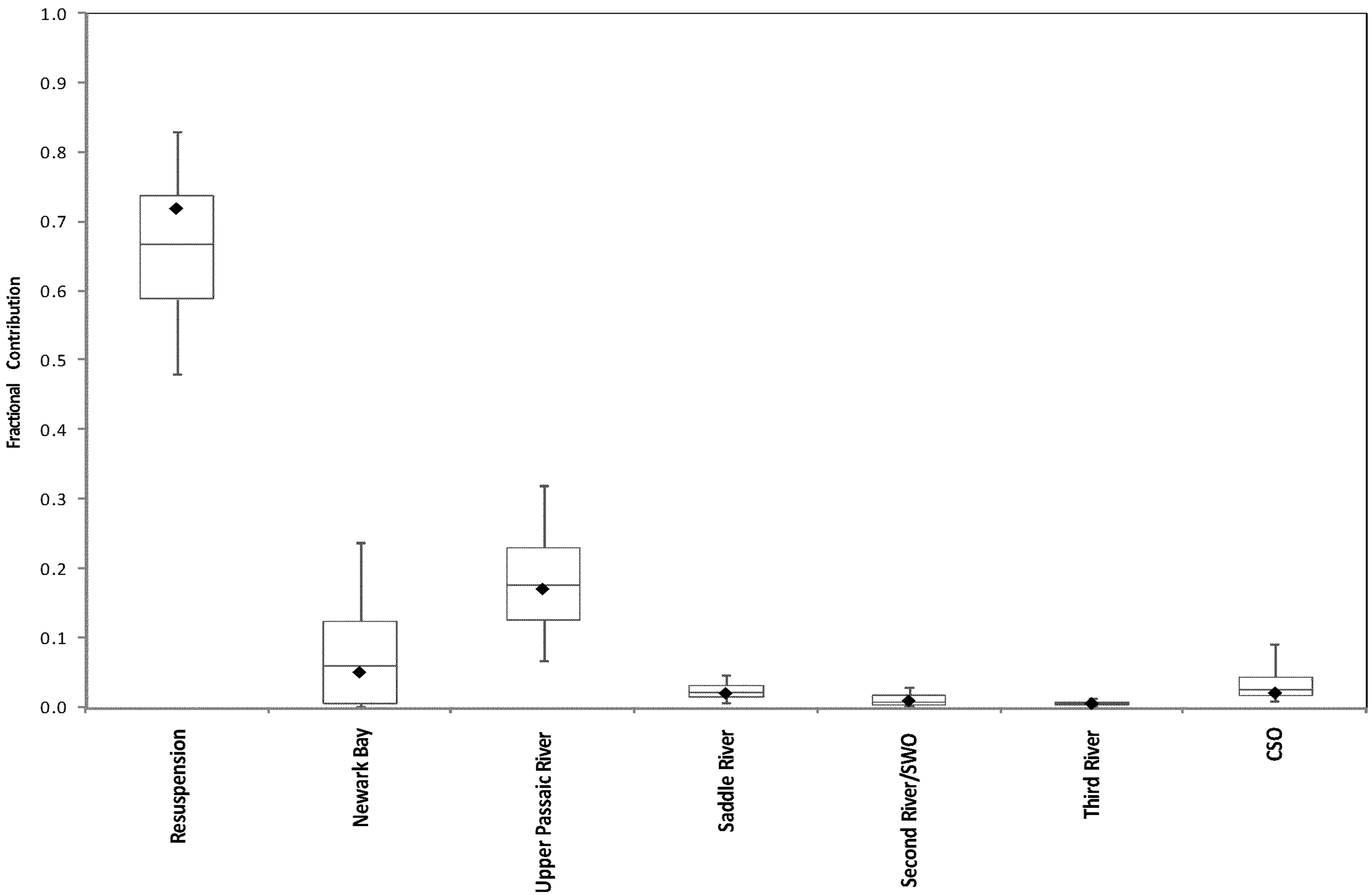
- Upper Passaic River
- Saddle River
- Second River/SWO
- Third River
- CSO
- Newark Bay Northern End
- Resuspension (Lower Passaic River)

Source Concentration and Mass Balance for Total Organic Carbon

Lower Eight Miles of the Lower Passaic River

Figure 4-15a

2014



Legend

- 95th Percentile
- 75th Percentile
- Best Estimate *
- 50th Percentile
- 25th Percentile
- 5th Percentile

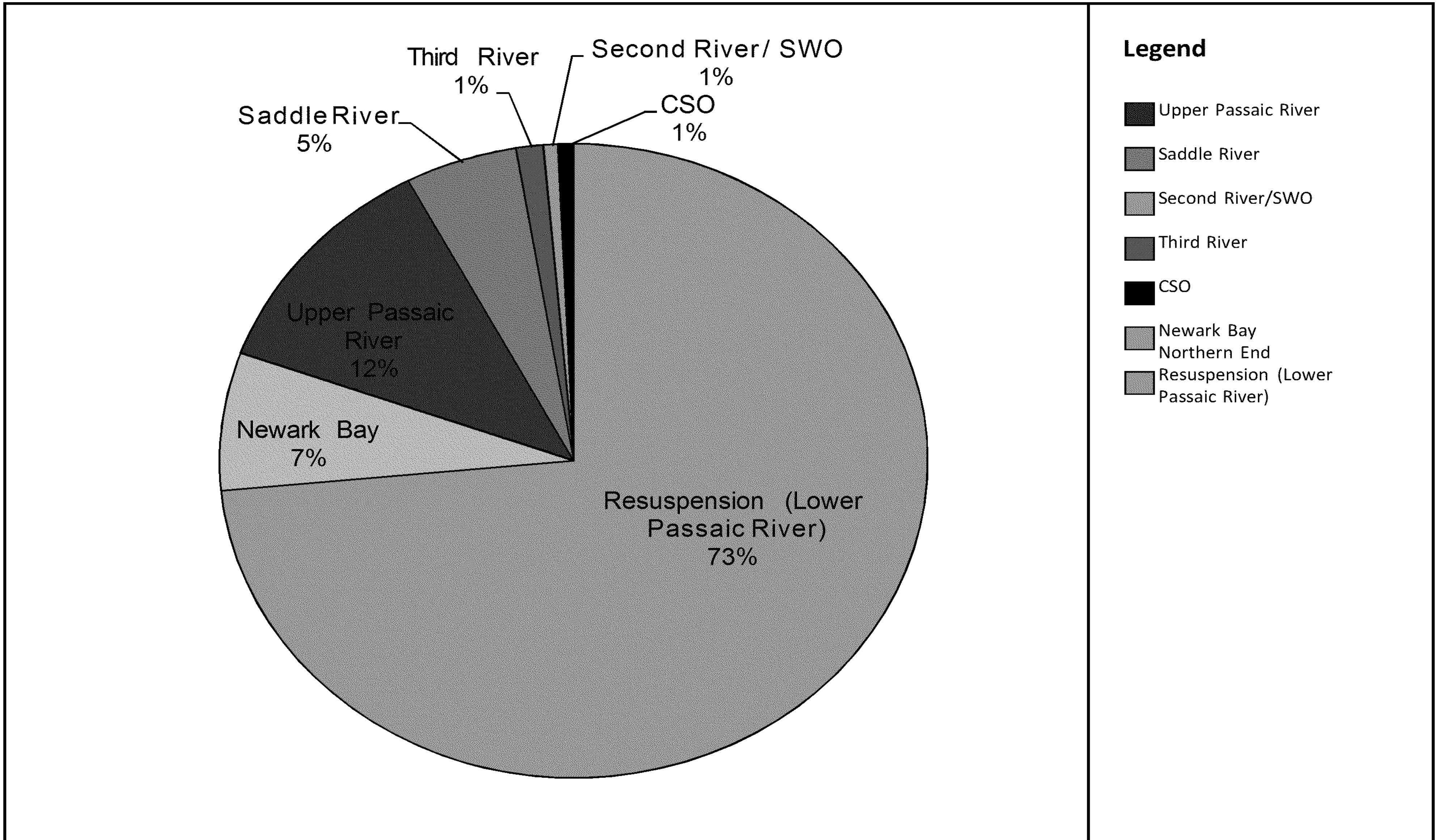
Notes:
*: Best Estimate represents Mass Balance estimates using average input values for source profiles.

5th, 25th, 50th, 75th and 95th percentiles are based on Mass Balance results for the 10,000 iterations in Monte Carlo Analysis.

Fractional Contribution for Total Organic Carbon
(Results from Monte Carlo Analysis and Best Estimate Solution)
Lower Eight Miles of the Lower Passaic River

Figure 4-15b

2014

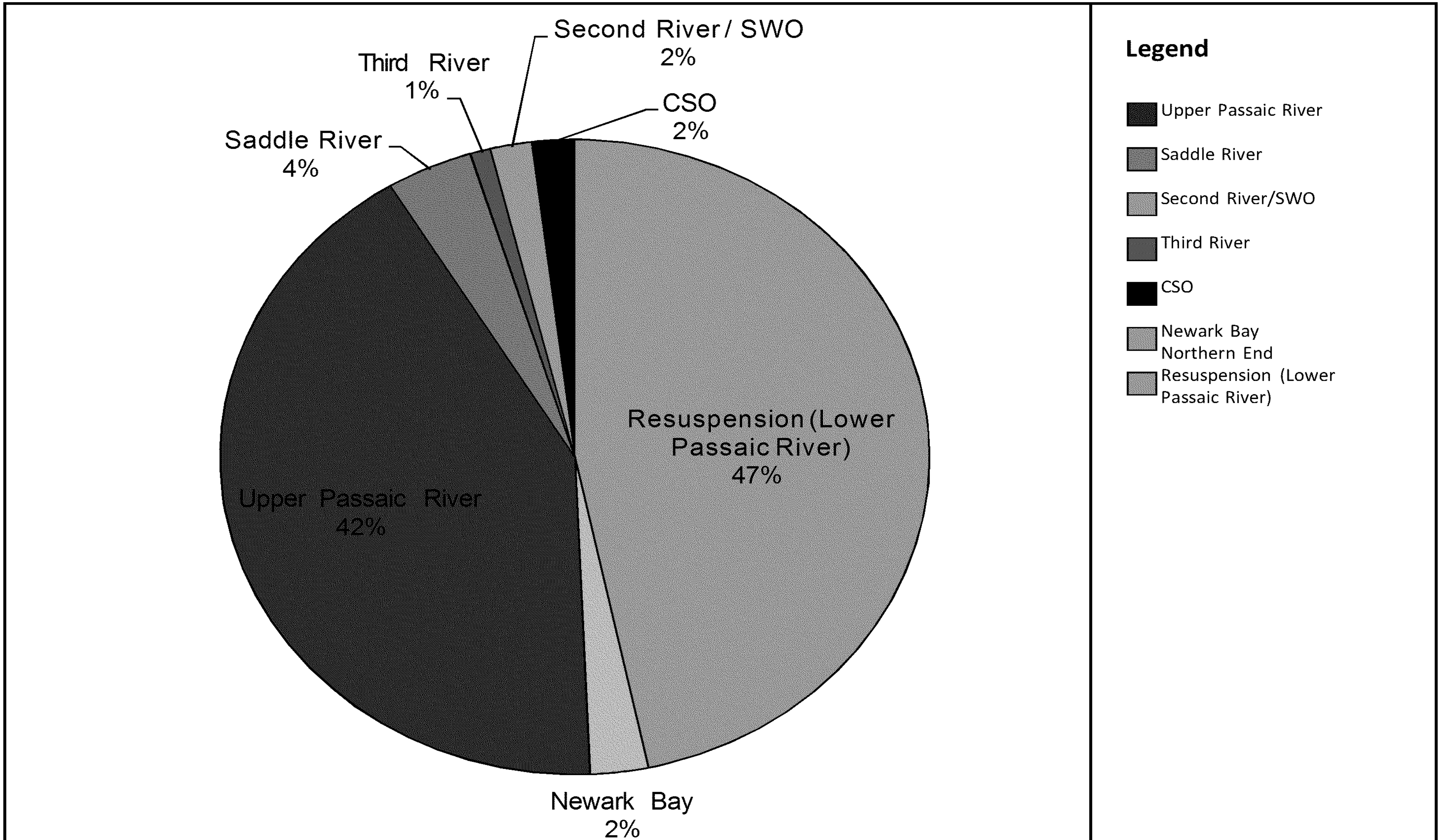


Dieldrin Contribution to the Lower Passaic River

Lower Eight Miles of the Lower Passaic River

Figure 4-16

2014

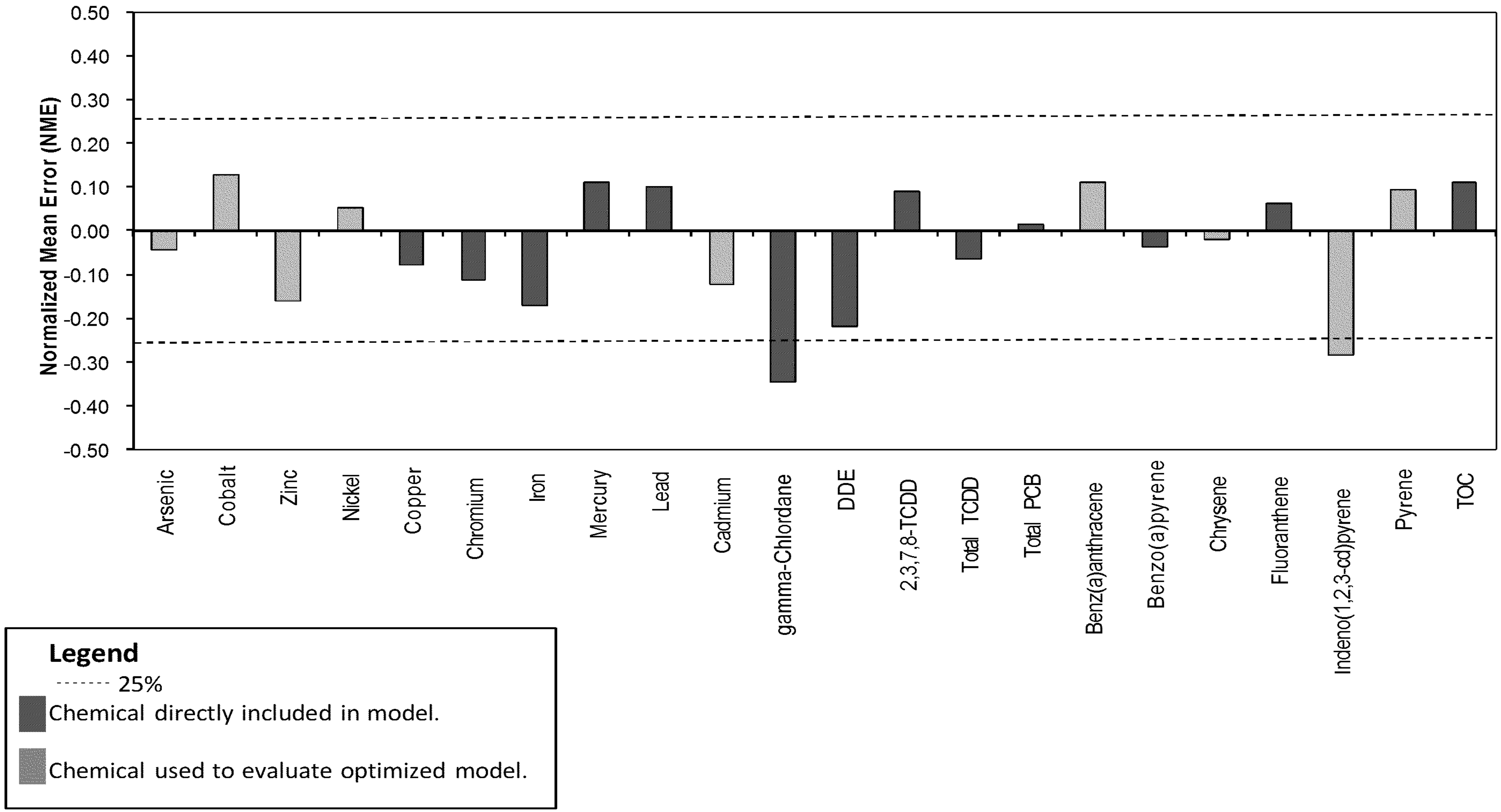


Phenanthrene Contribution to the Lower Passaic River

Lower Eight Miles of the Lower Passaic River

Figure 4-17

2014

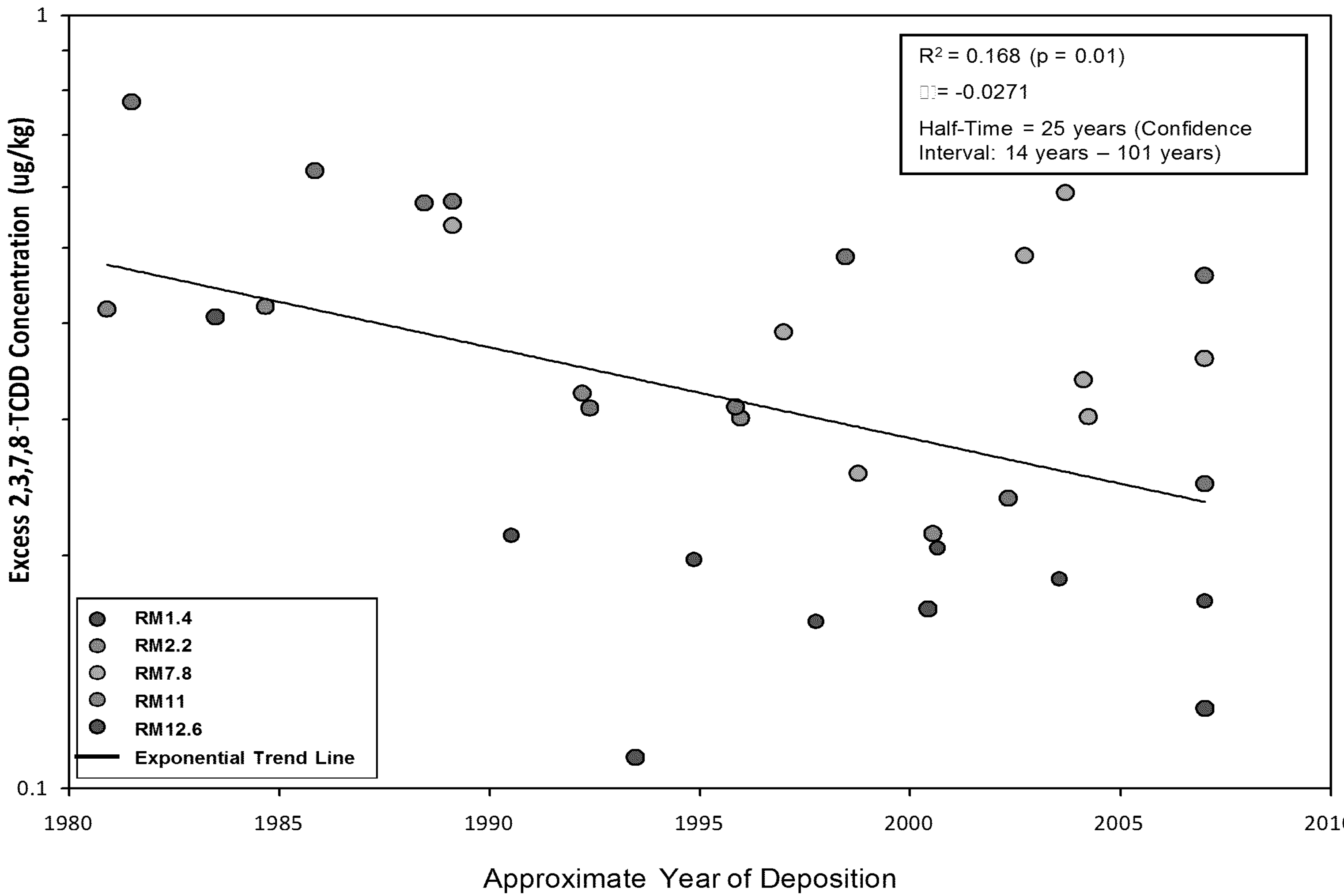


Evaluation of EMB Model Performance

Lower Eight Miles of the Lower Passaic River

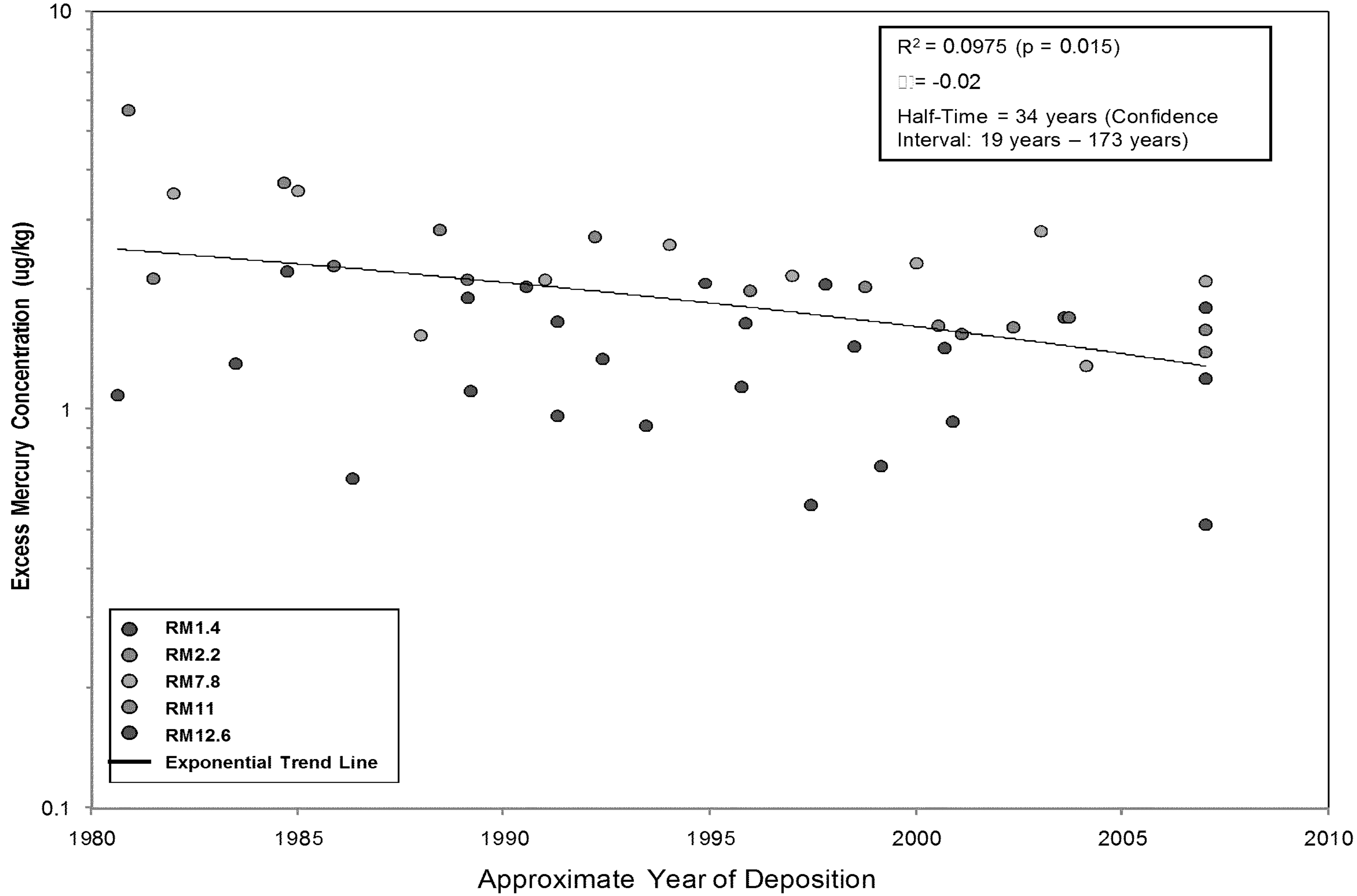
Figure 4-18

2014



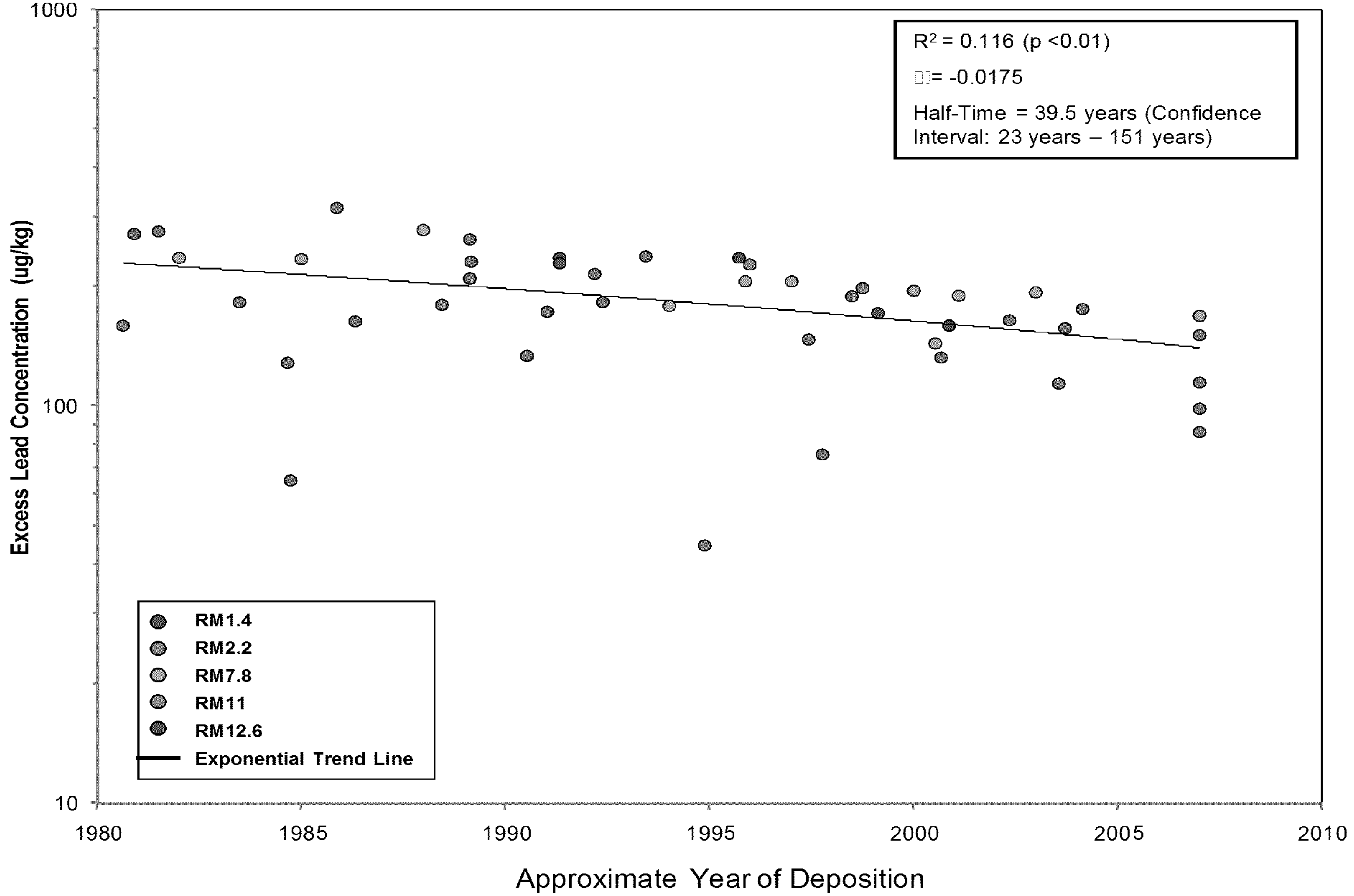
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess 2,3,7,8-TCDD Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-1 2014



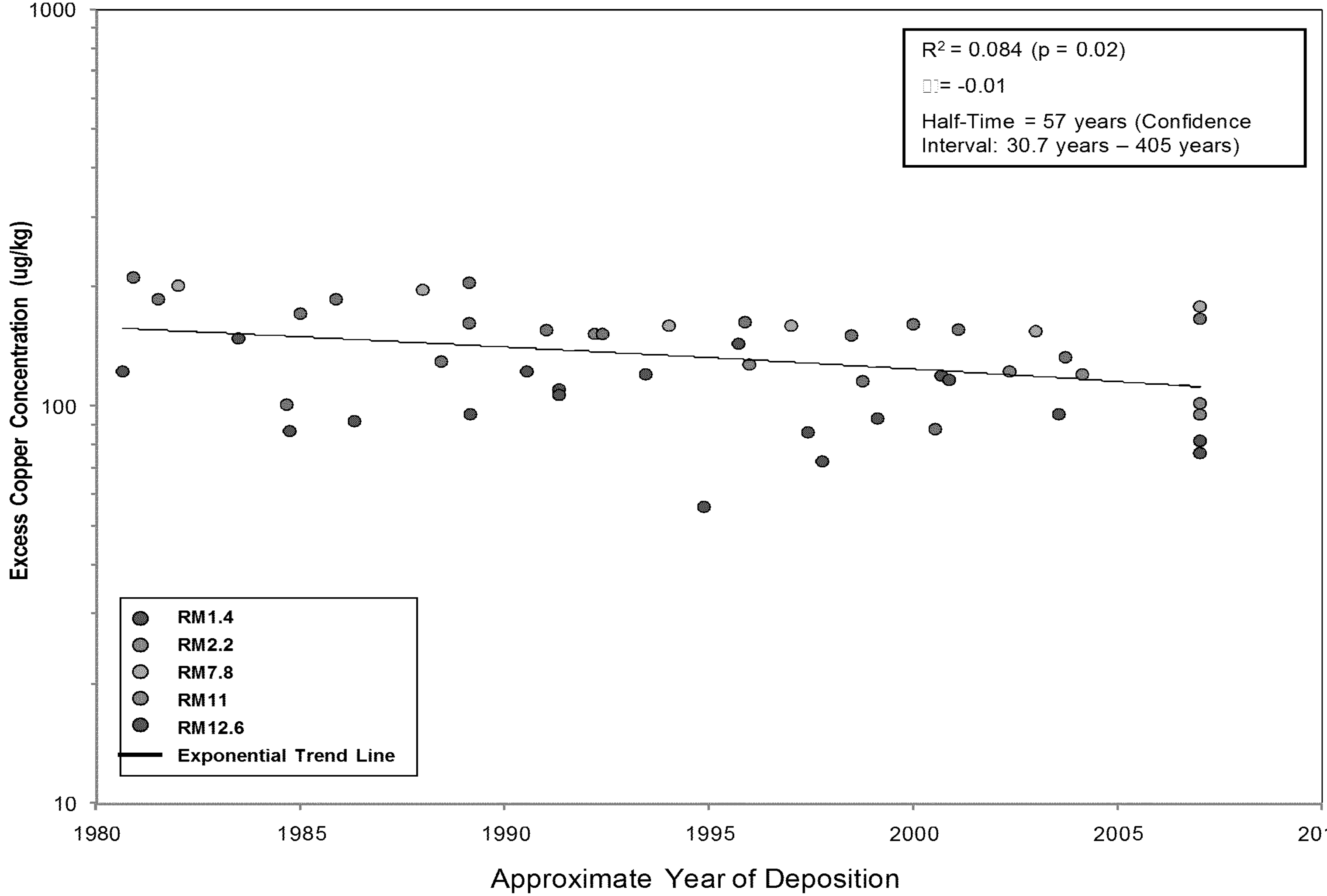
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess Mercury Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-2 2014



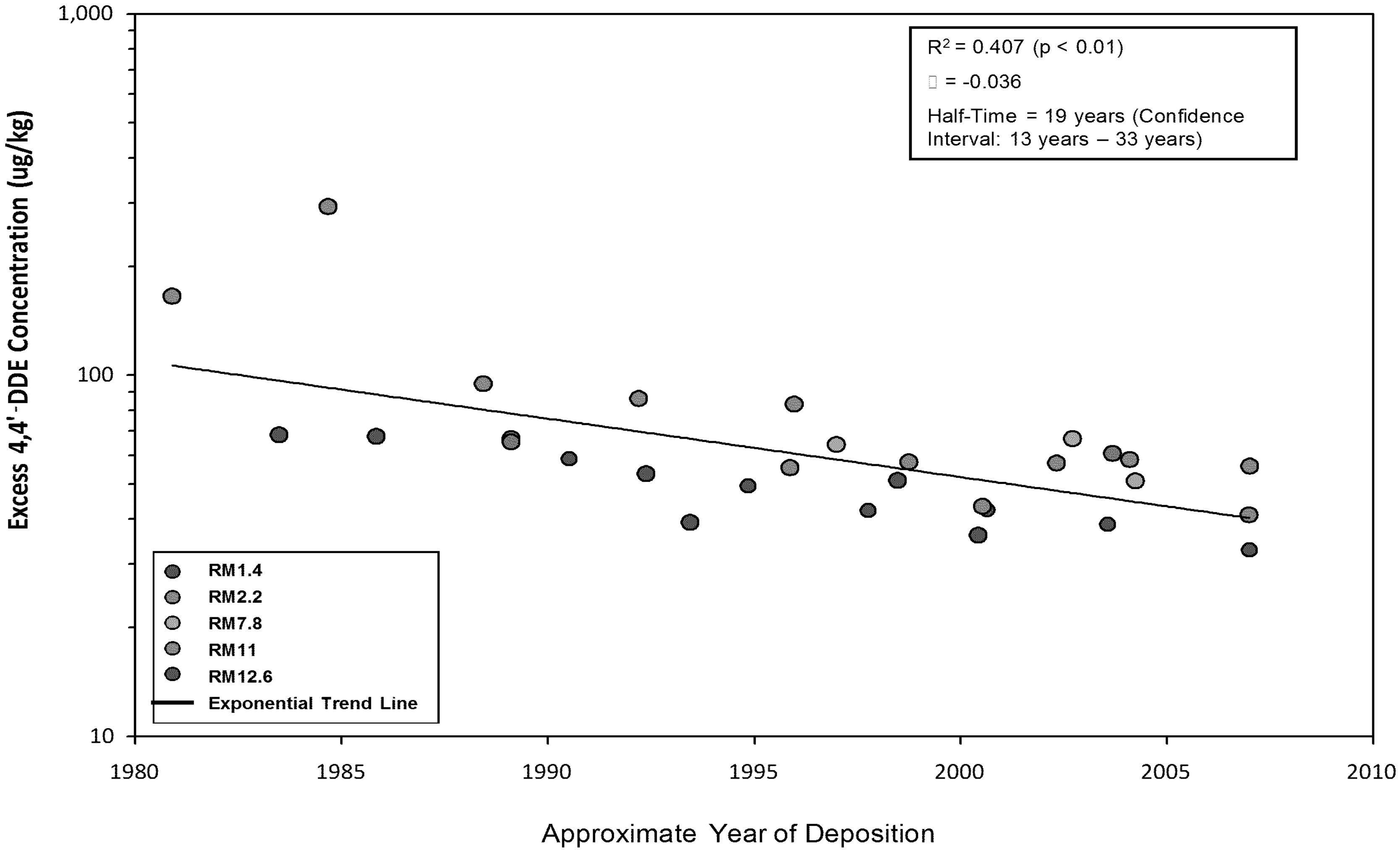
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess Lead Concentration *vs.* Approximate Year of Deposition	Figure 5-3
	Lower Eight Miles of the Lower Passaic River	2014



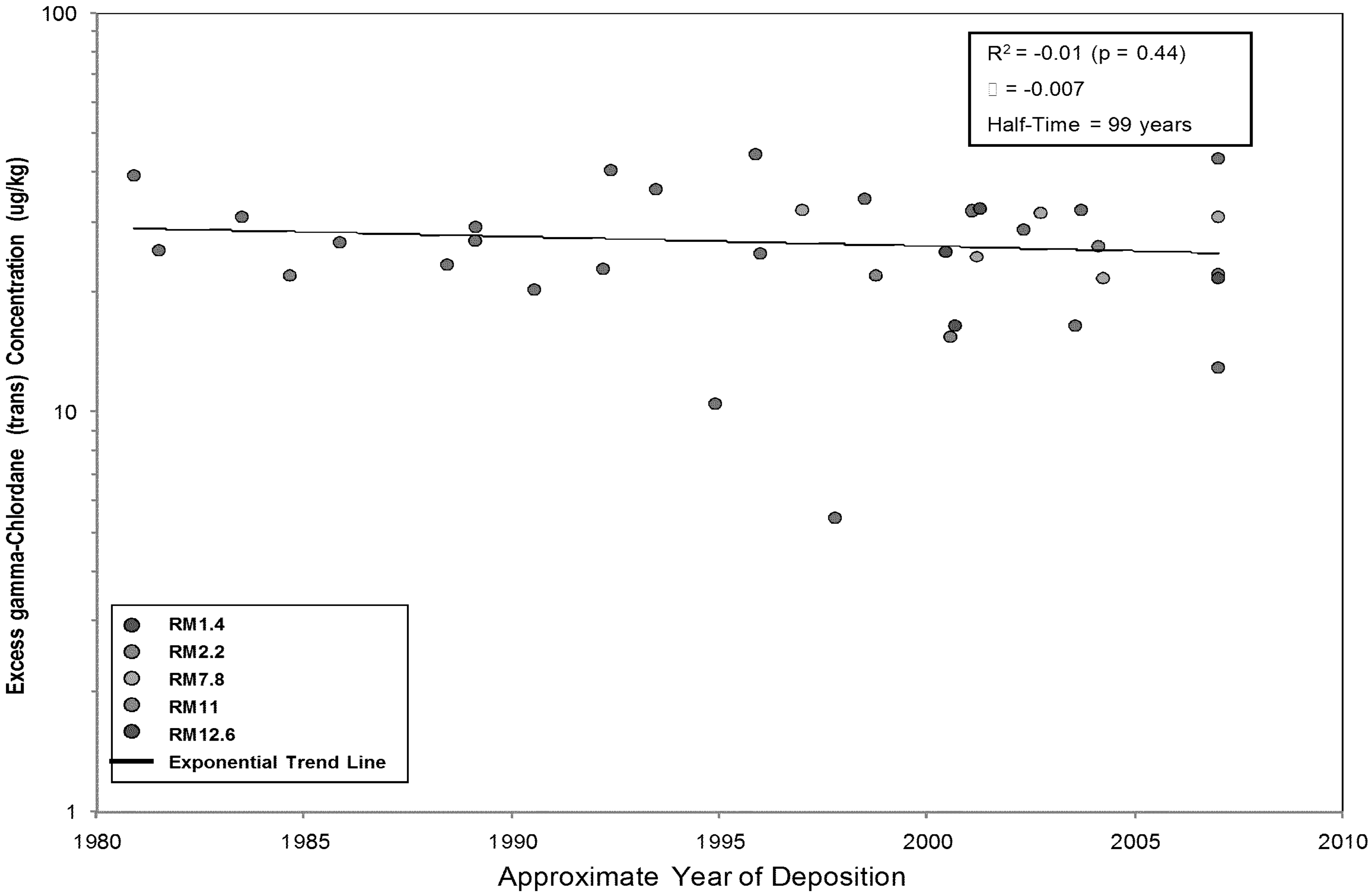
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess Copper Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-4 2014



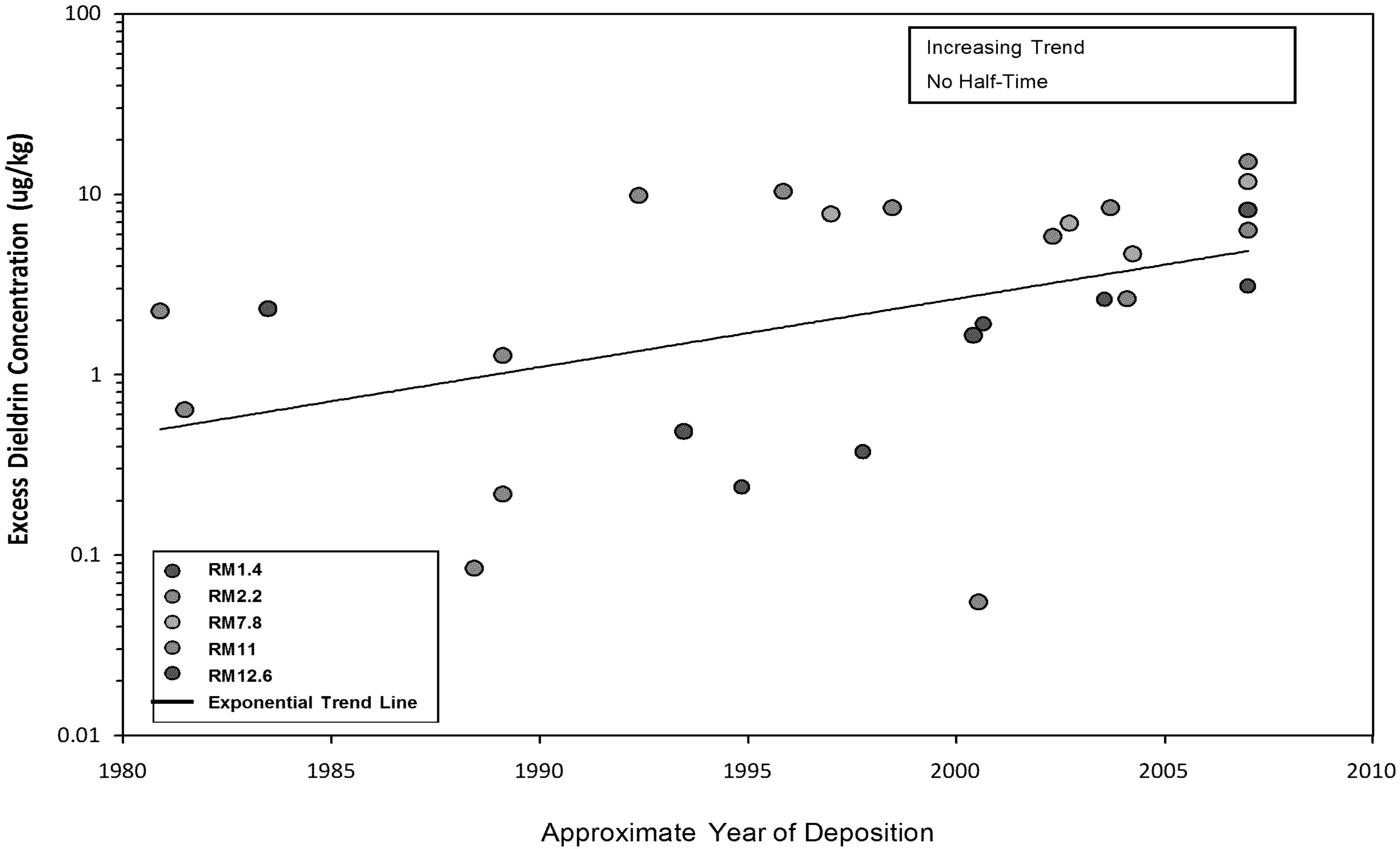
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess 4,4'-DDE Concentration *vs.* Approximate Year of Deposition	Figure 5-5
	Lower Eight Miles of the Lower Passaic River	2014



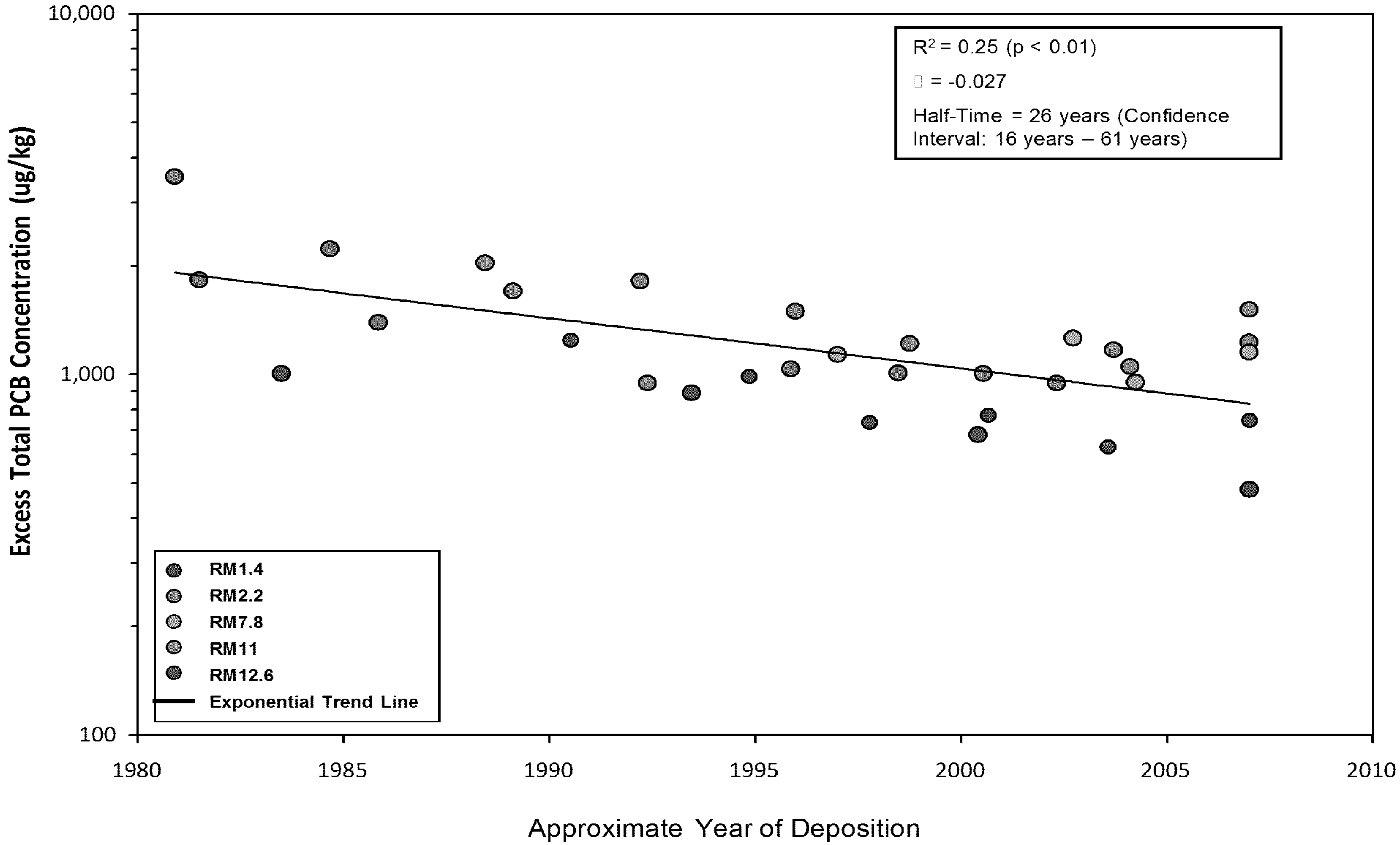
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess gamma-Chlordane Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-6 2014



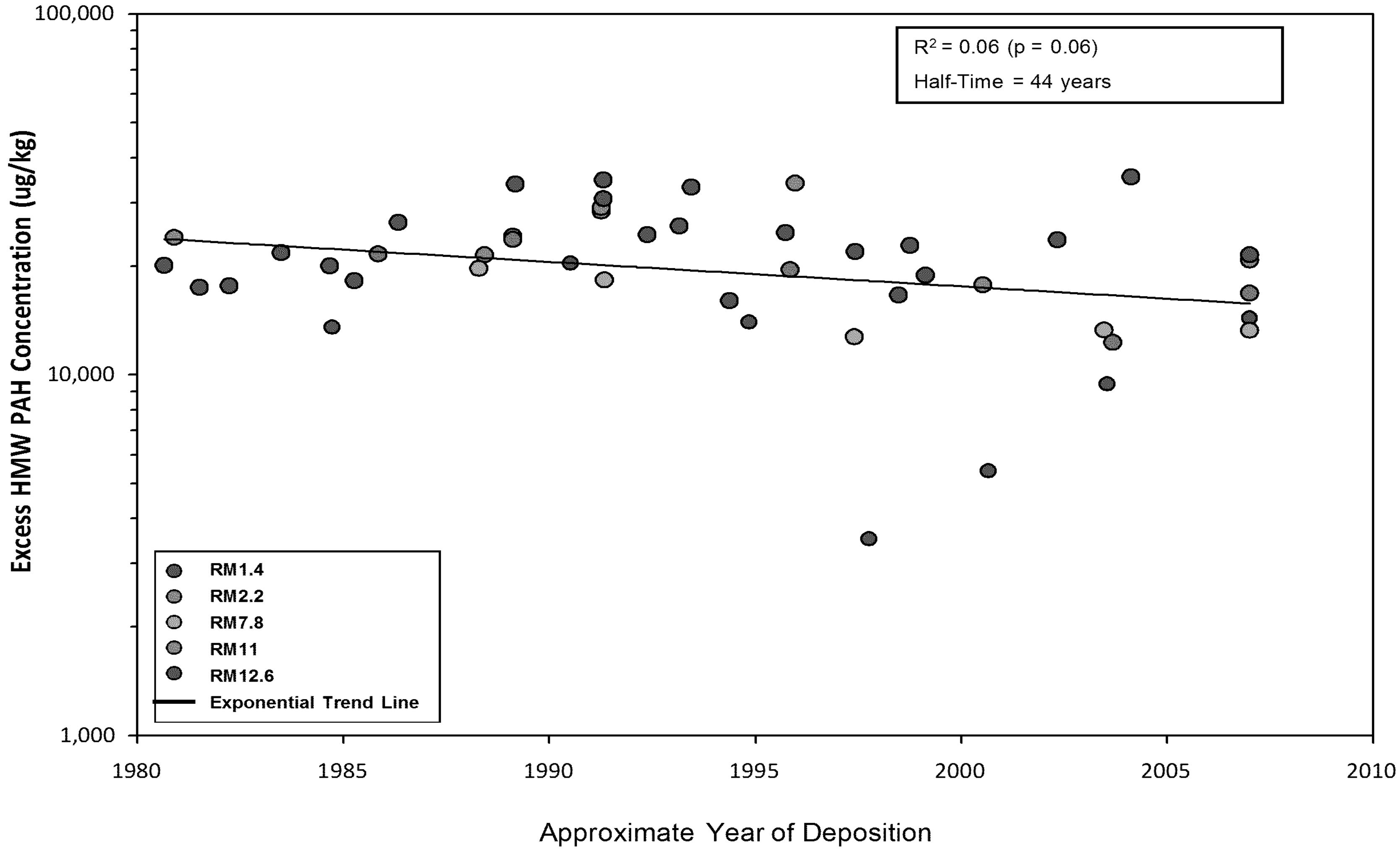
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess Dieldrin Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-7 2014



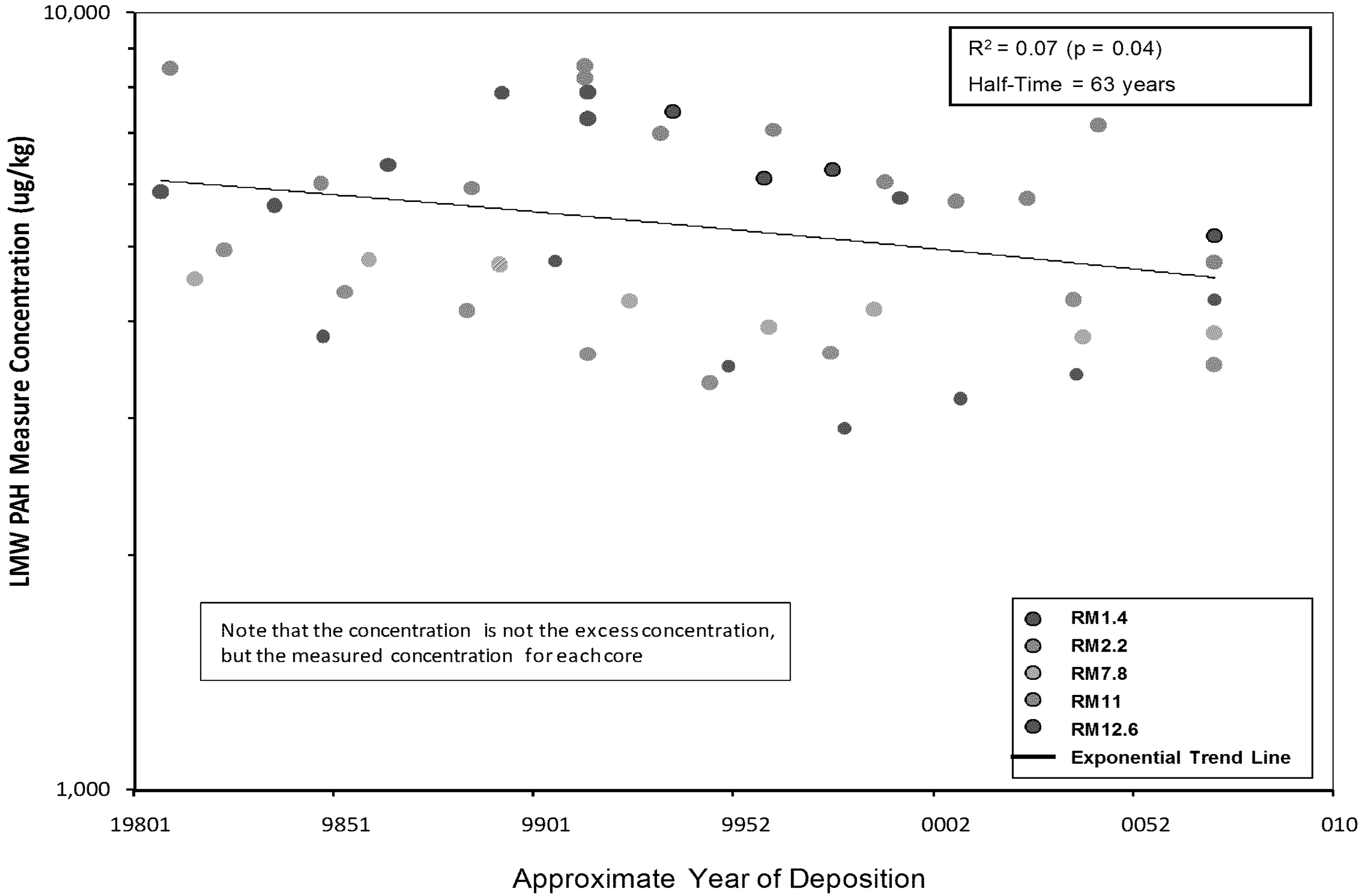
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess Total PCBs Concentration *vs.* Approximate Year of Deposition	Figure 5-8
	Lower Eight Miles of the Lower Passaic River	2014



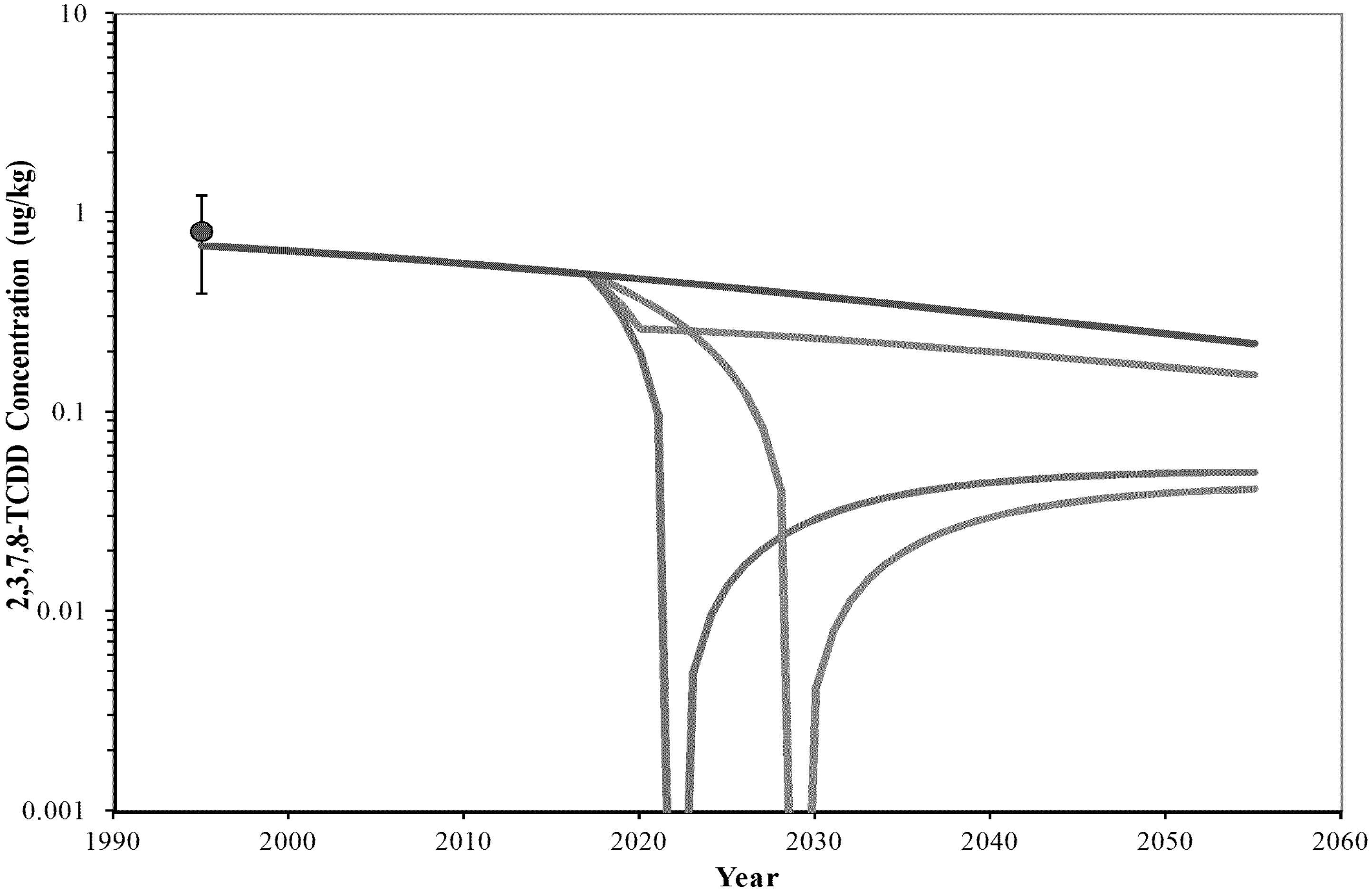
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess High Molecular Weight PAH Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-9 2014

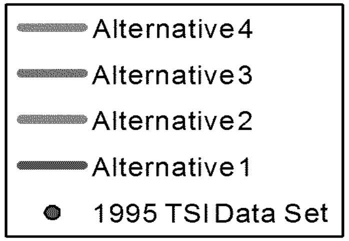


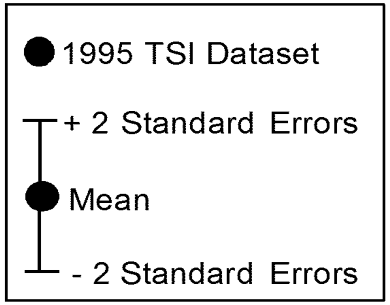
Note:
Excess concentration represents the difference between the measured concentration in the Lower Passaic River recently deposited (Be-7 bearing) samples and the baseline concentration. The excess is attributed to resuspension and Newark Bay derived loads.

	Excess Low Molecular Weight PAH Concentration *vs.* Approximate Year of Deposition *Lower Eight Miles of the Lower Passaic River*	Figure 5-10 2014



Legend





Note

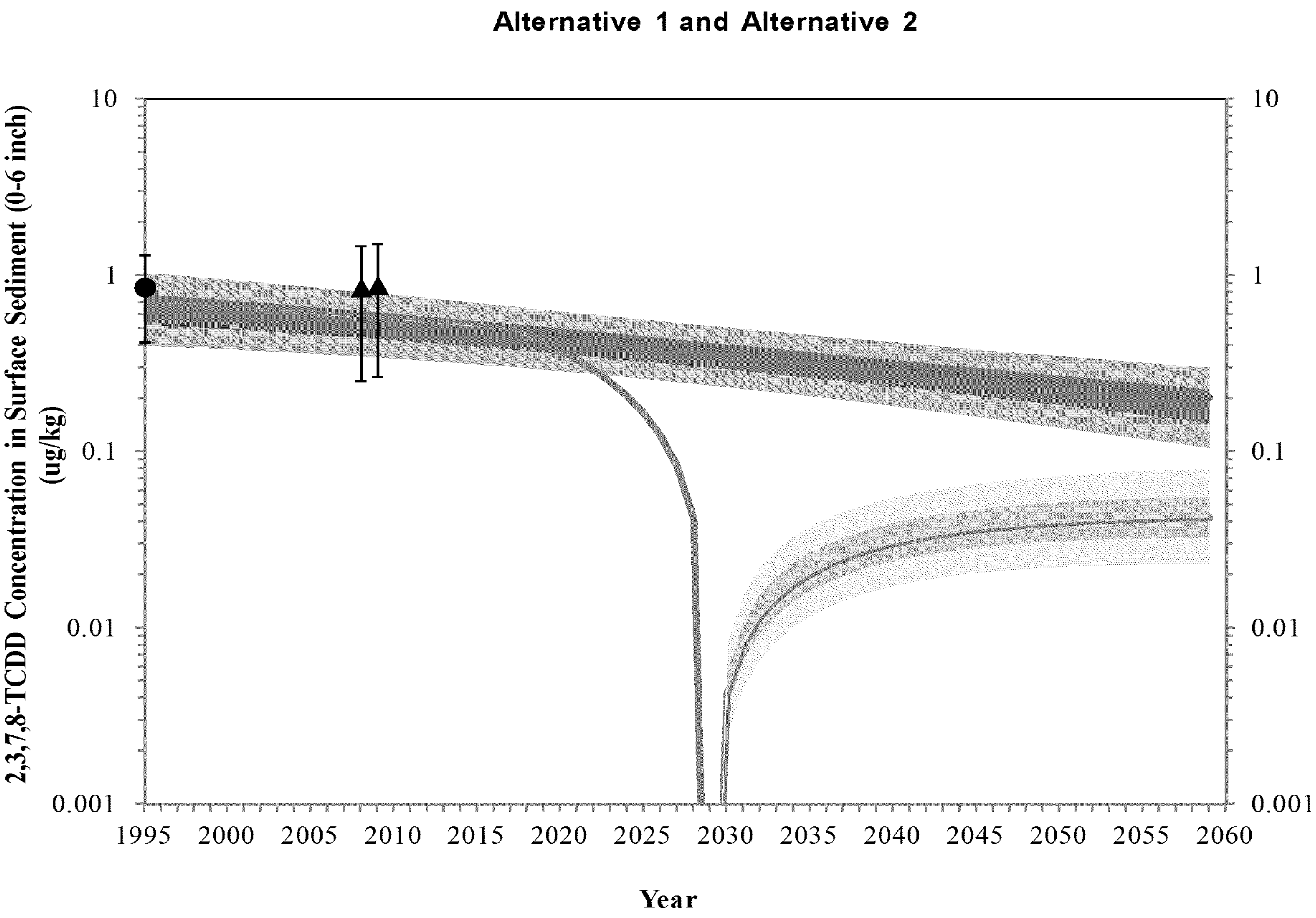
Best Estimate represents trajectory results using average input values for all parameters.

2,3,7,8-TCDD Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-11a

2014



Legend

Alternative 1

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 2

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

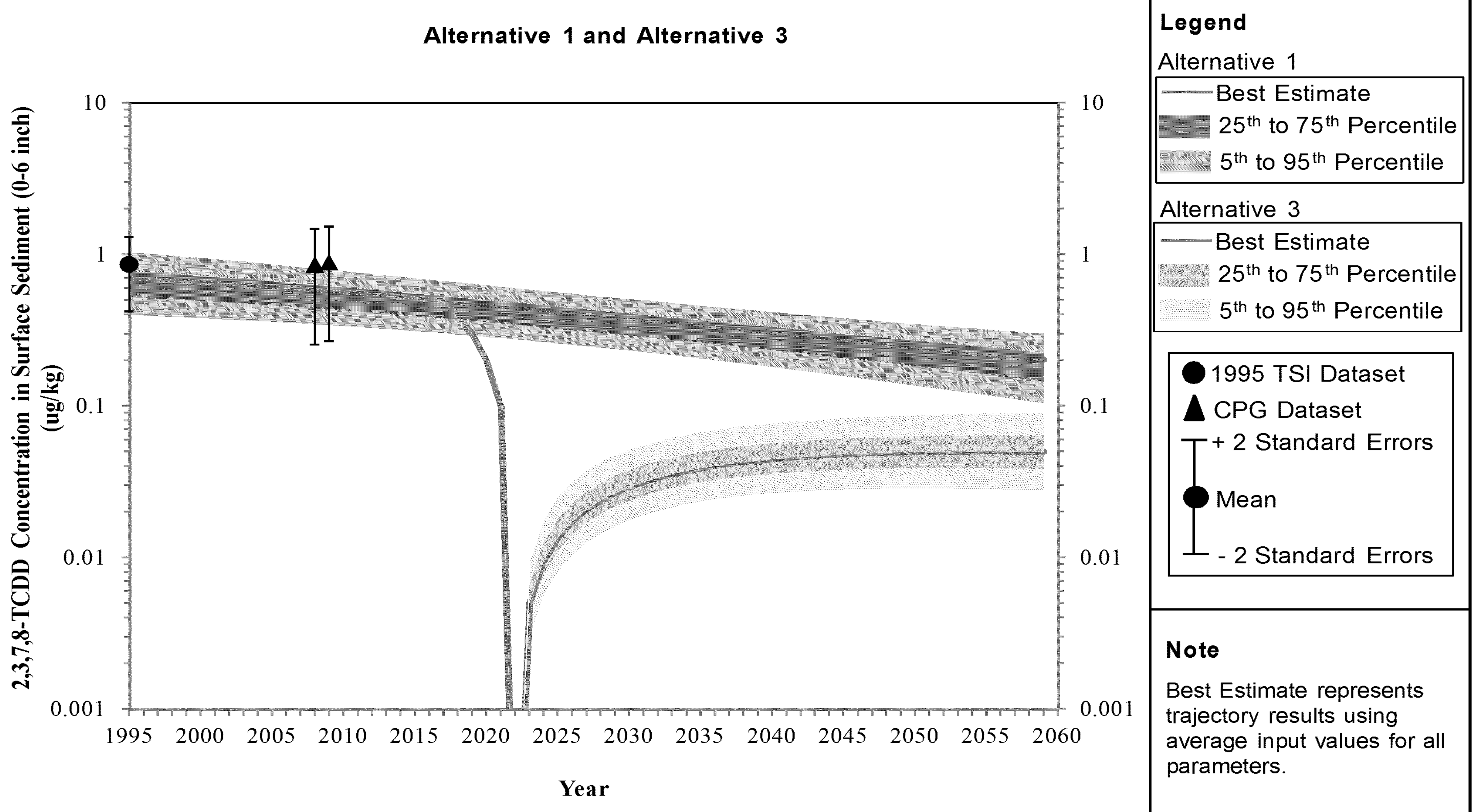
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for 2,3,7,8-TCDD Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2)

Lower Eight Miles of the Lower Passaic River

Figure 5-11b

2014



Note

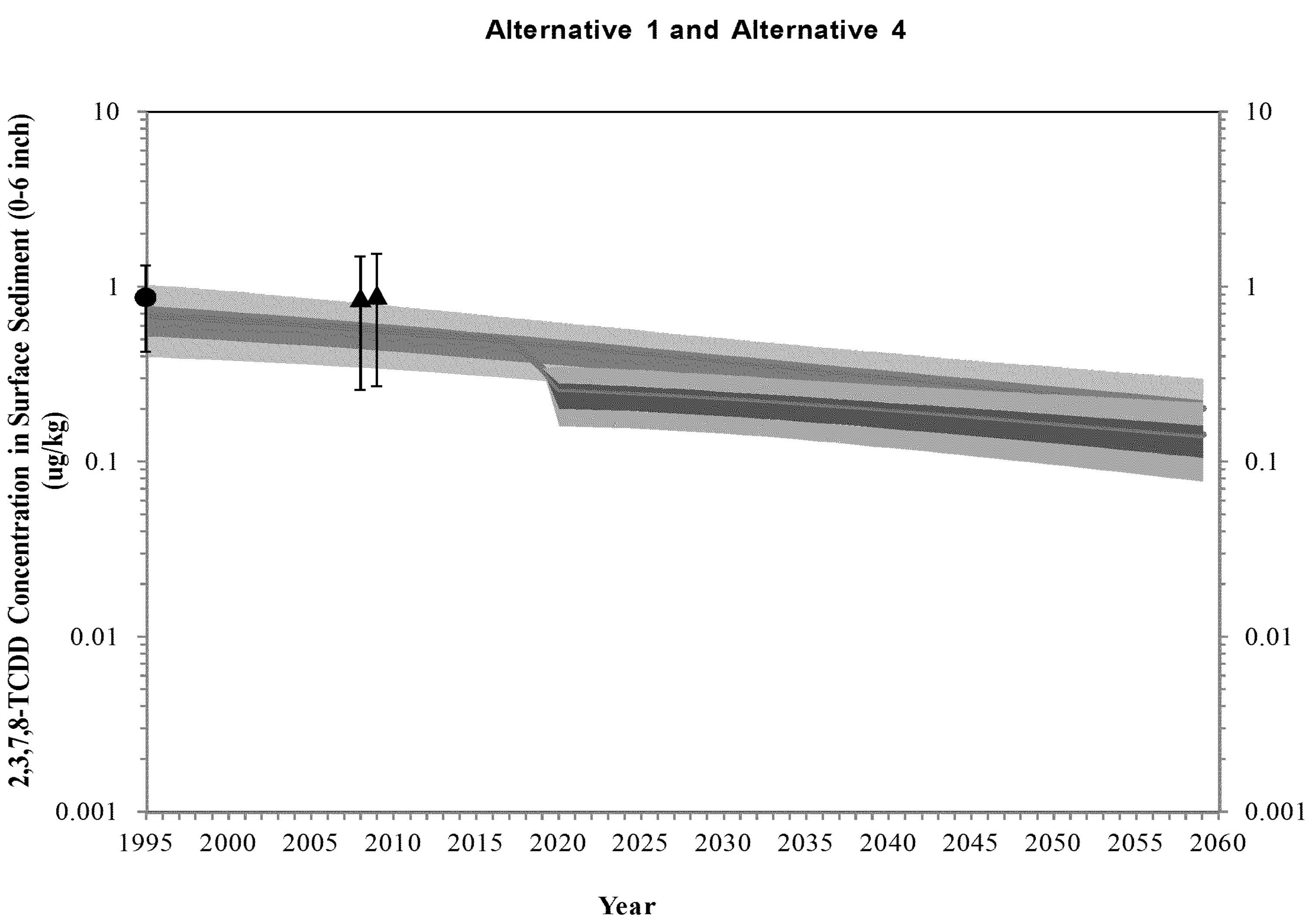
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for 2,3,7,8-TCDD Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3)

Lower Eight Miles of the Lower Passaic River

Figure 5-11c

2014



Legend

Alternative 1
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 4
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- \+ 2 Standard Errors
- Mean
- \- 2 Standard Errors

Note

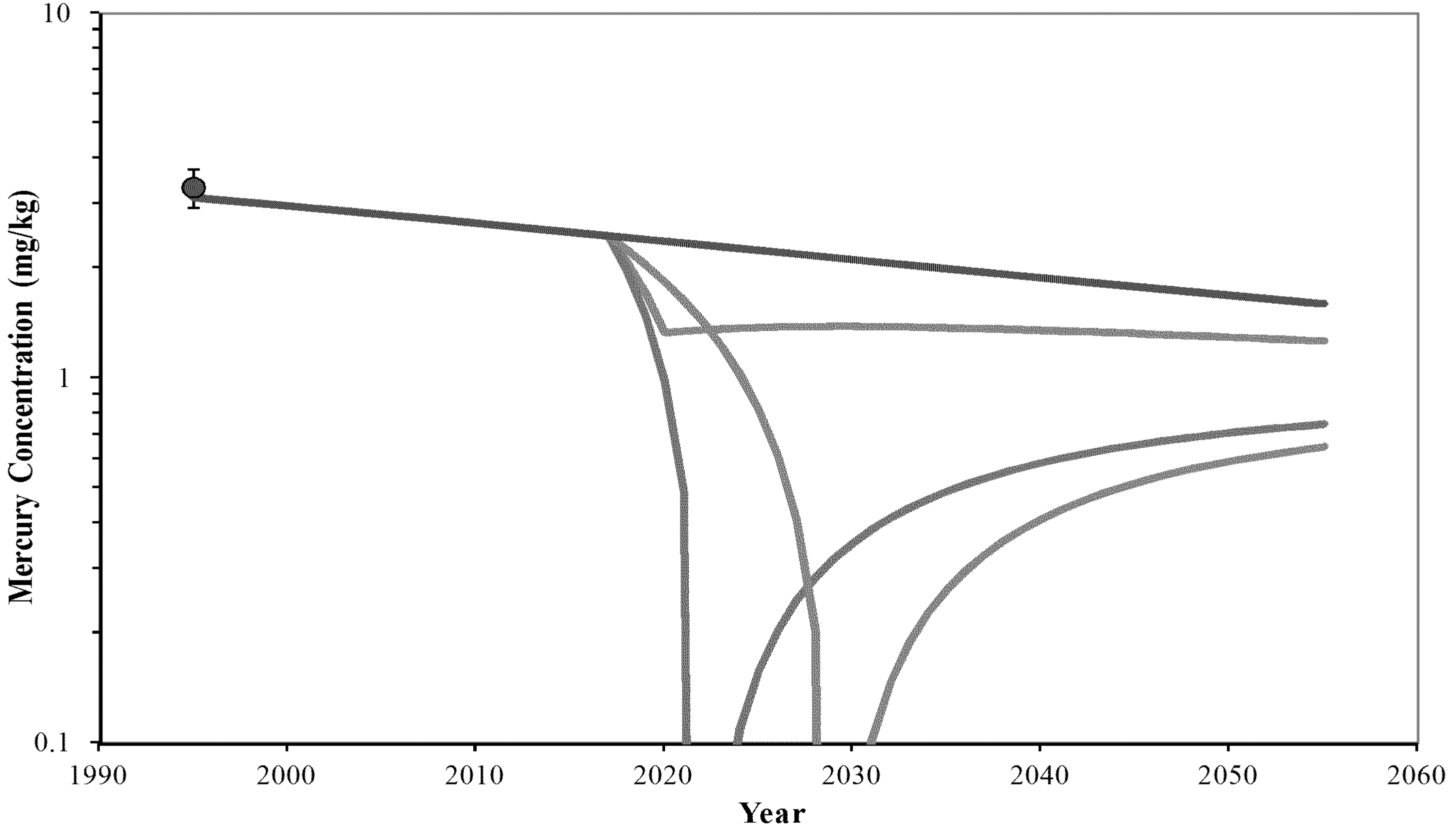
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for 2,3,7,8-TCDD Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

Lower Eight Miles of the Lower Passaic River

Figure 5-11d

2014



Legend

- Alternative 4
- Alternative 3
- Alternative 2
- Alternative 1
- 1995 TSI Data Set

1995 TSI Dataset
+ 2 Standard Errors
Mean
- 2 Standard Errors

Note

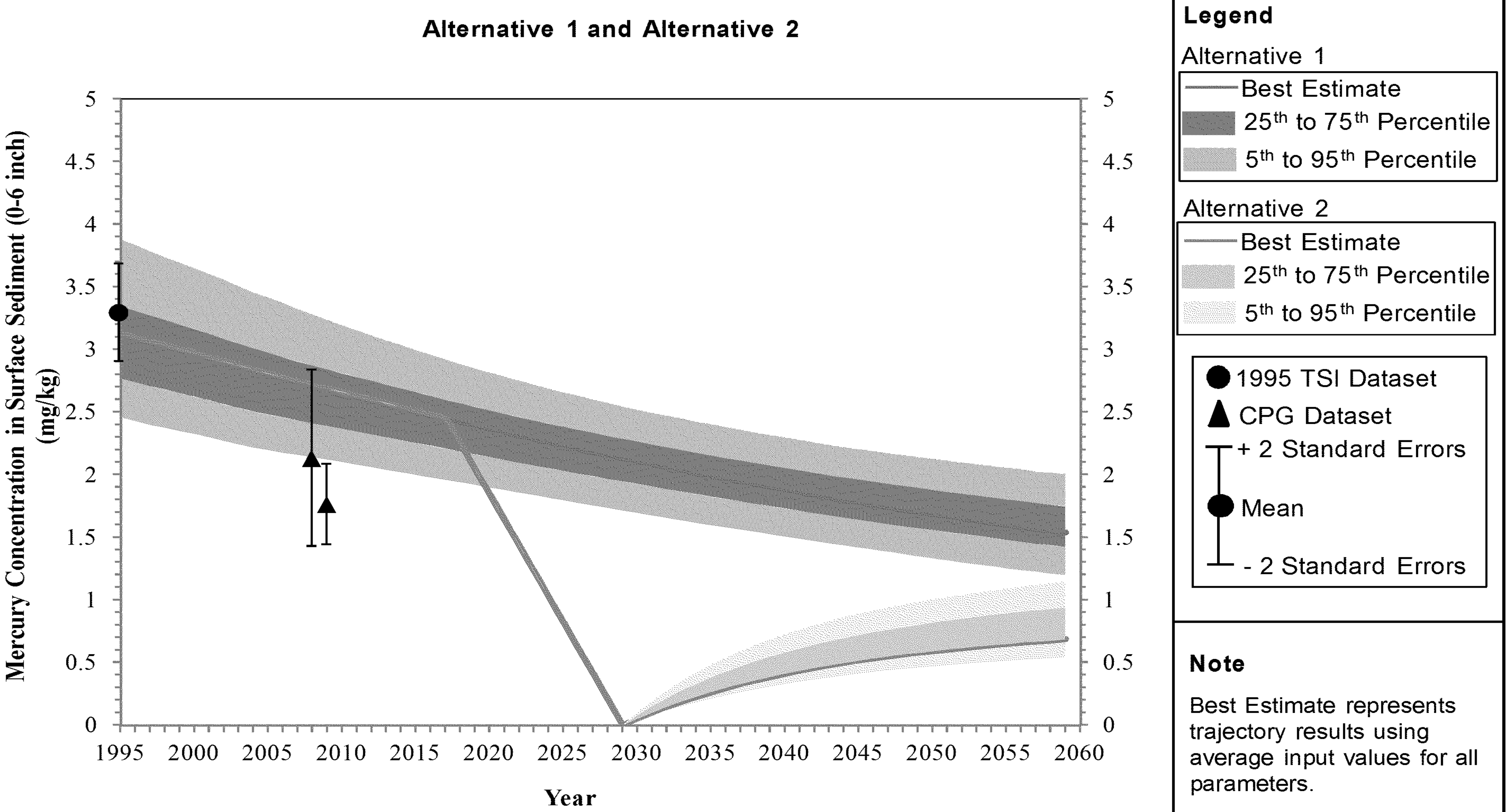
Best Estimate represents trajectory results using average input values for all parameters.

Mercury Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-12a

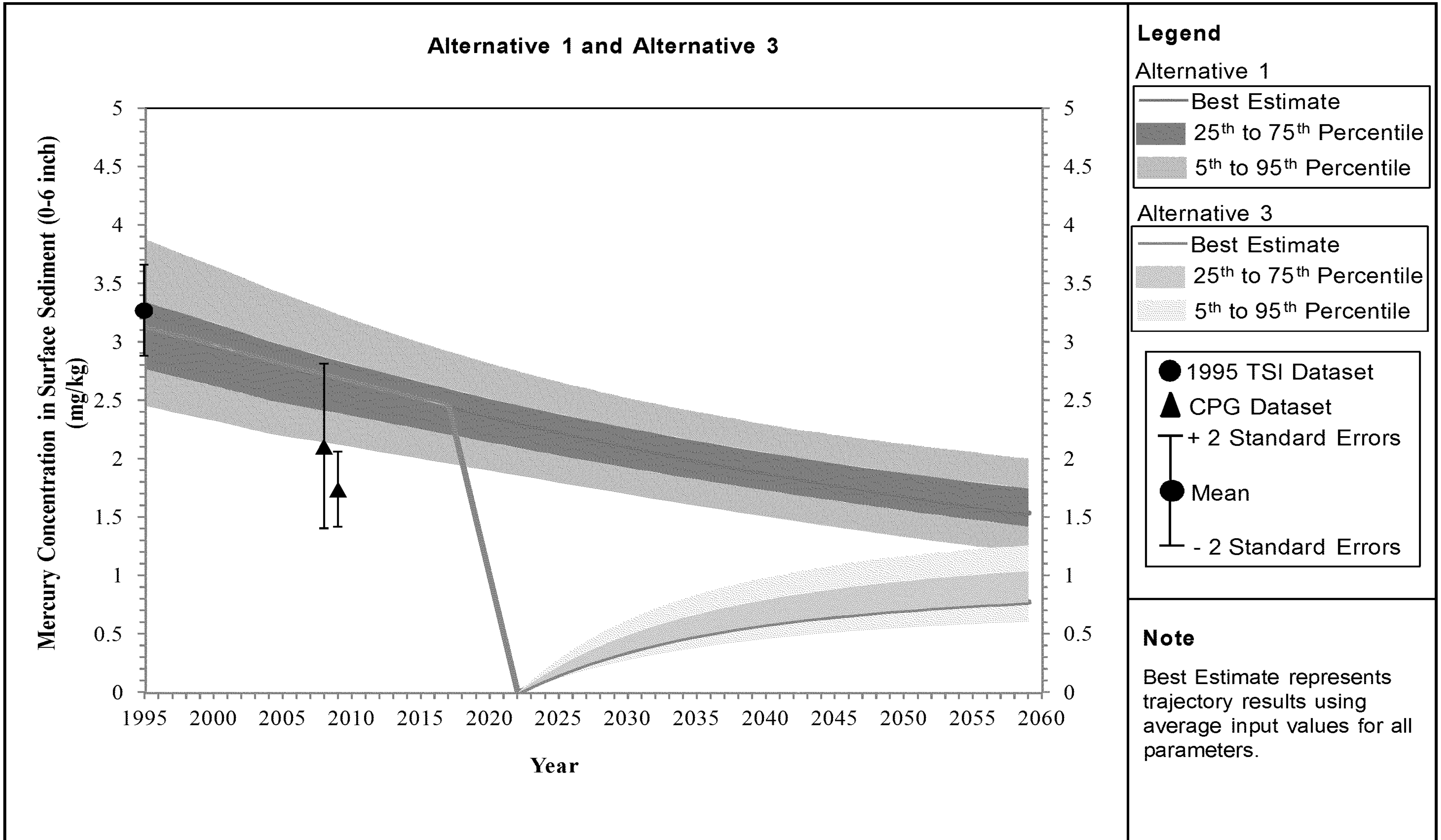
2014



Note

Best Estimate represents trajectory results using average input values for all parameters.

	Monte Carlo Trajectory Results for Mercury Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2) *Lower Eight Miles of the Lower Passaic River*	Figure 5-12b 2014



Note

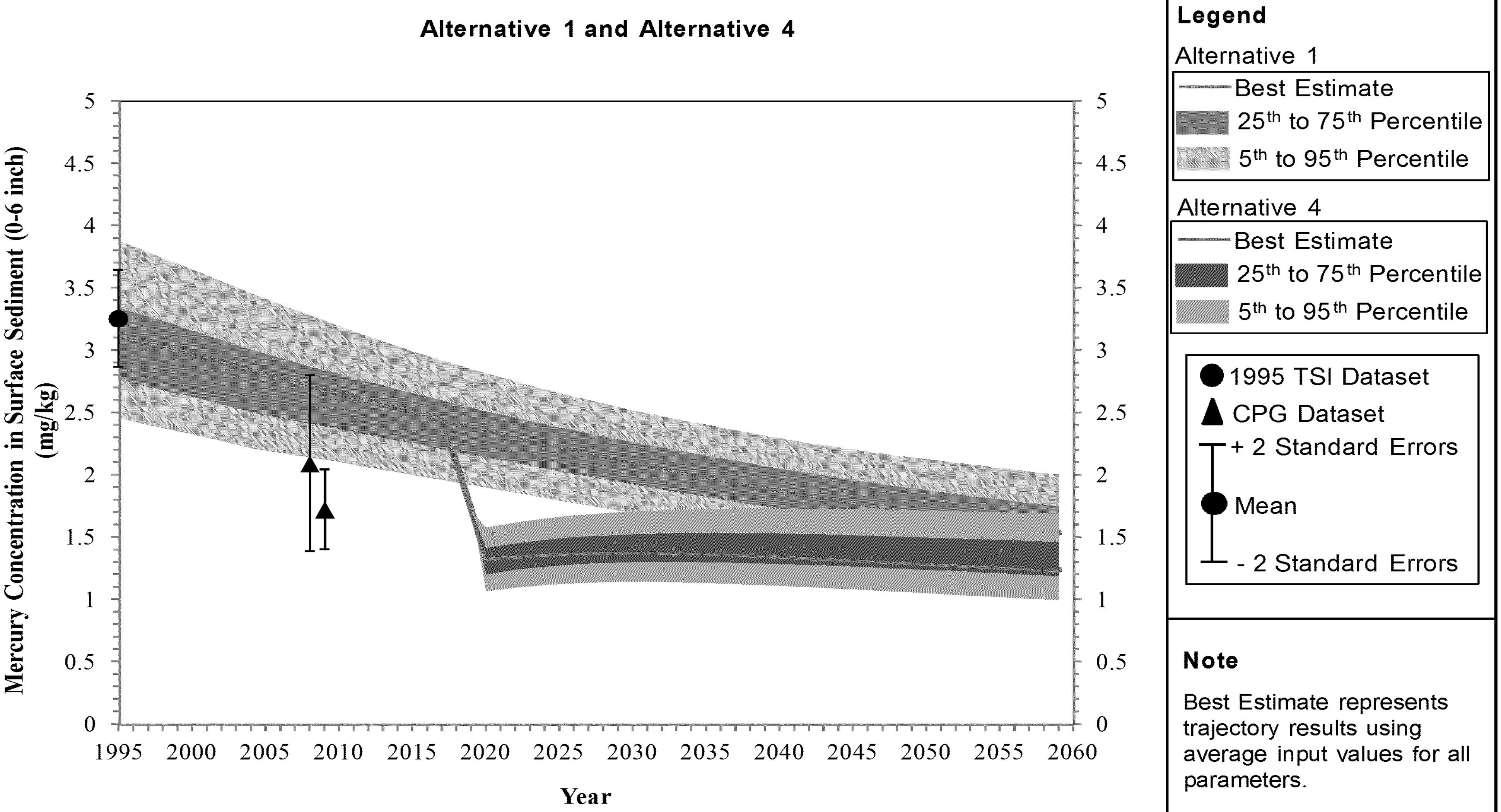
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Mercury Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3)

Lower Eight Miles of the Lower Passaic River

Figure 5-12c

2014



Note

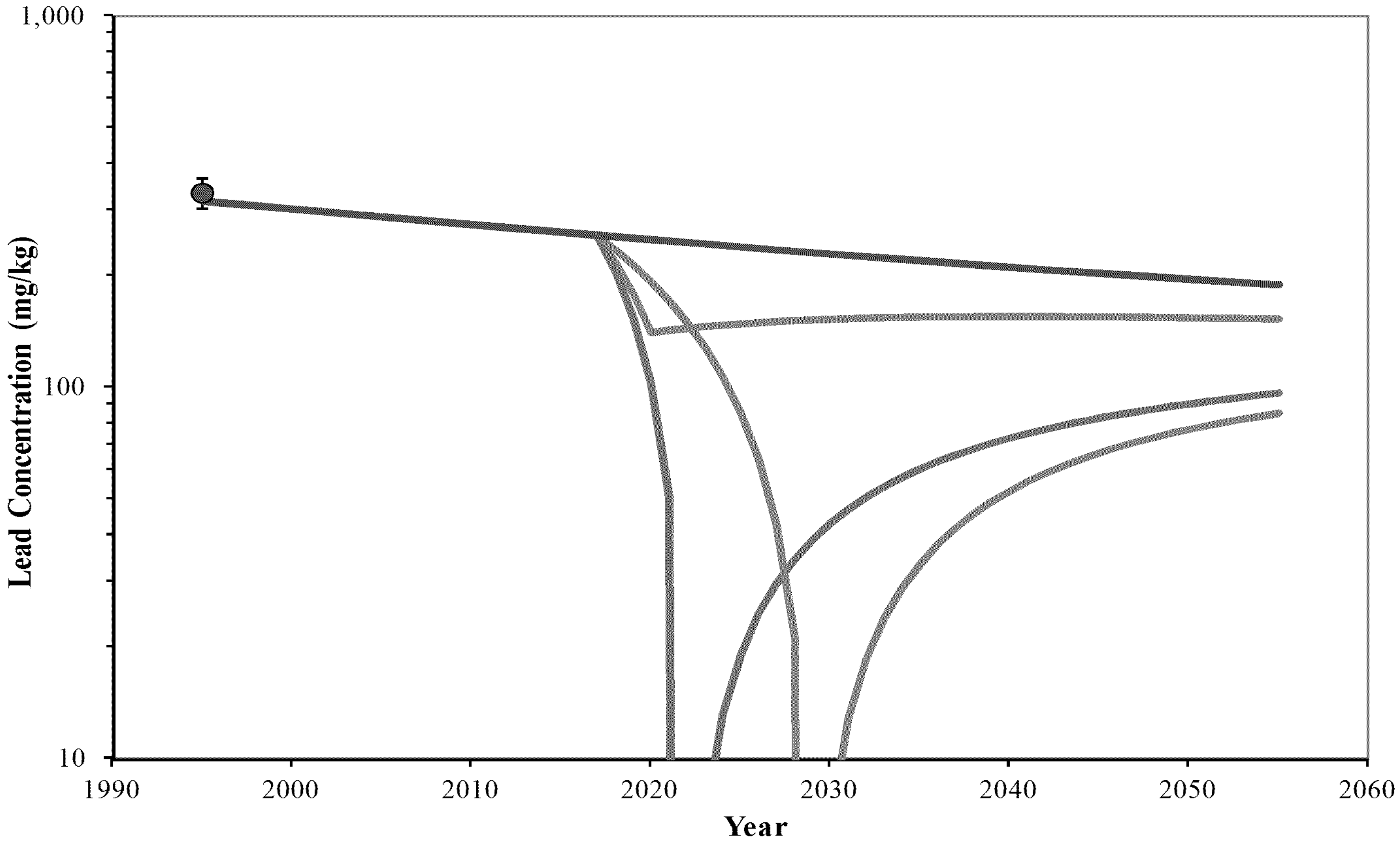
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Mercury Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

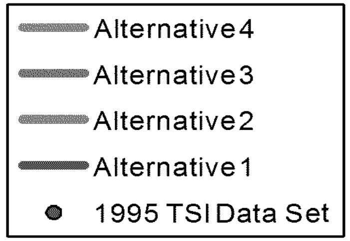
Lower Eight Miles of the Lower Passaic River

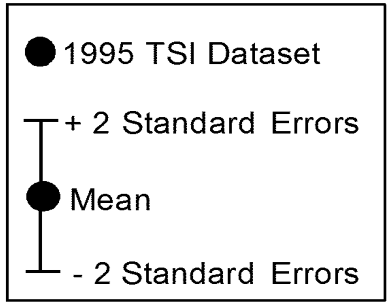
Figure 5-12d

2014



Legend





Note

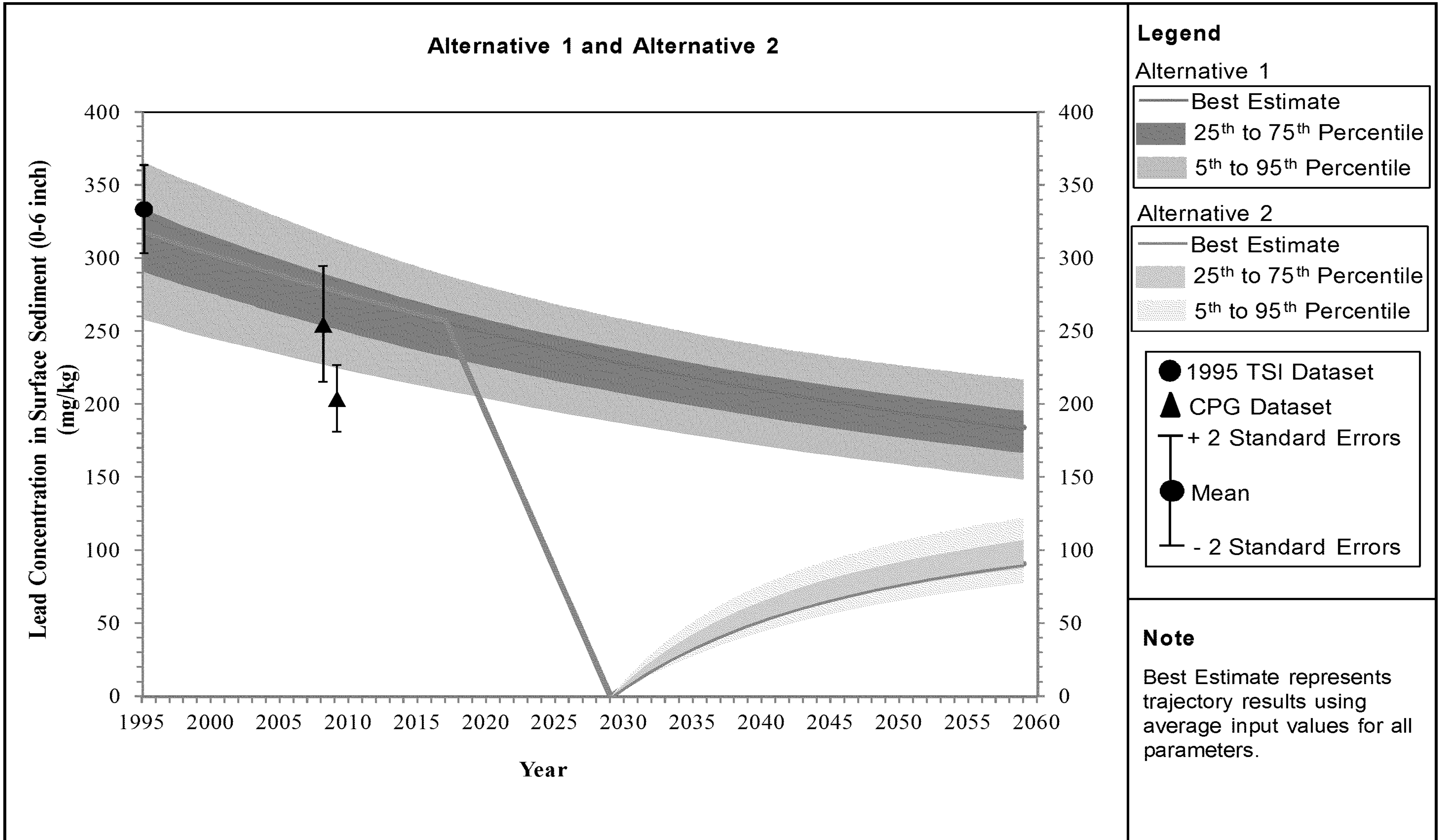
Best Estimate represents trajectory results using average input values for all parameters.

Lead Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-13a

2014



Note

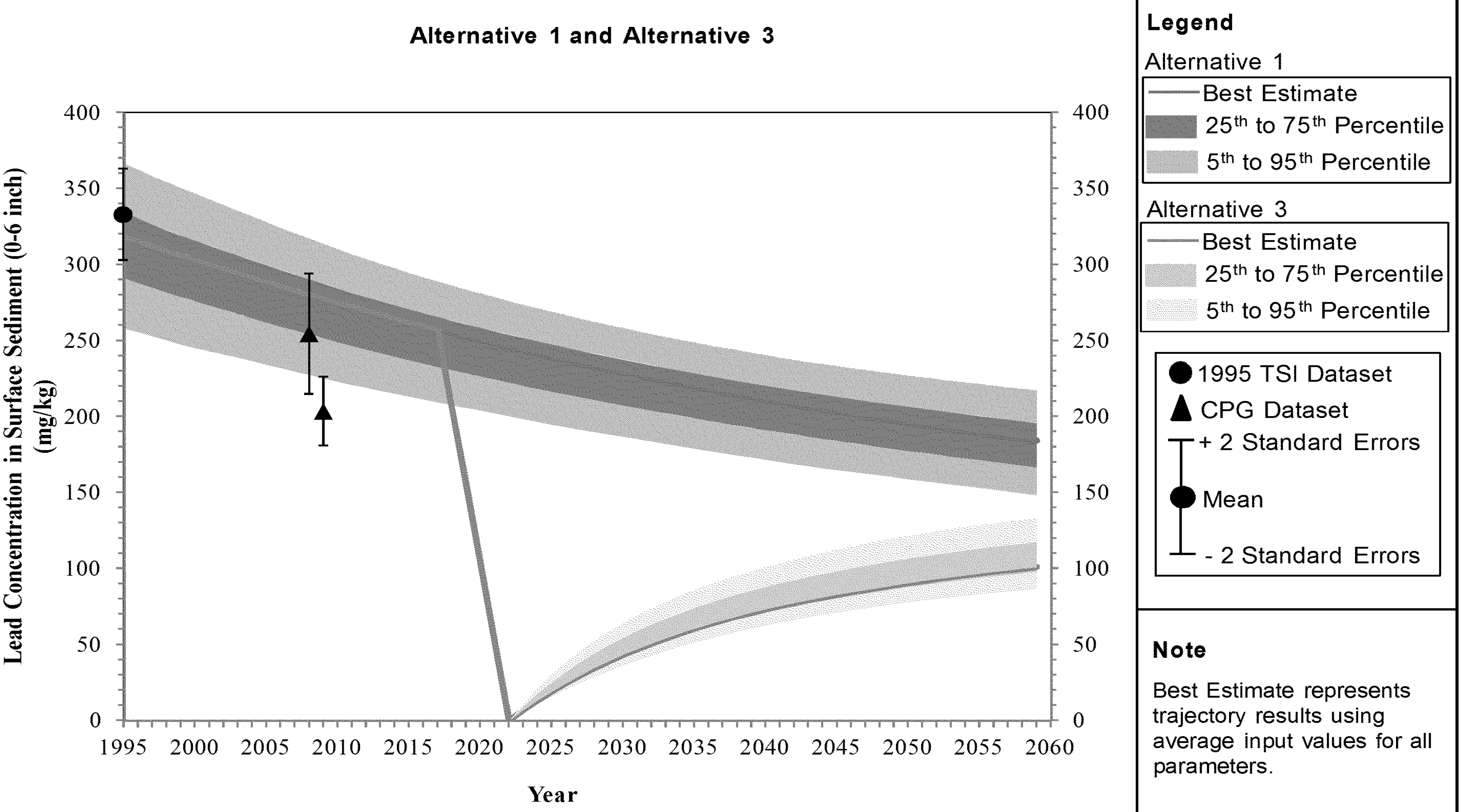
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Lead Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2)

Lower Eight Miles of the Lower Passaic River

Figure 5-13b

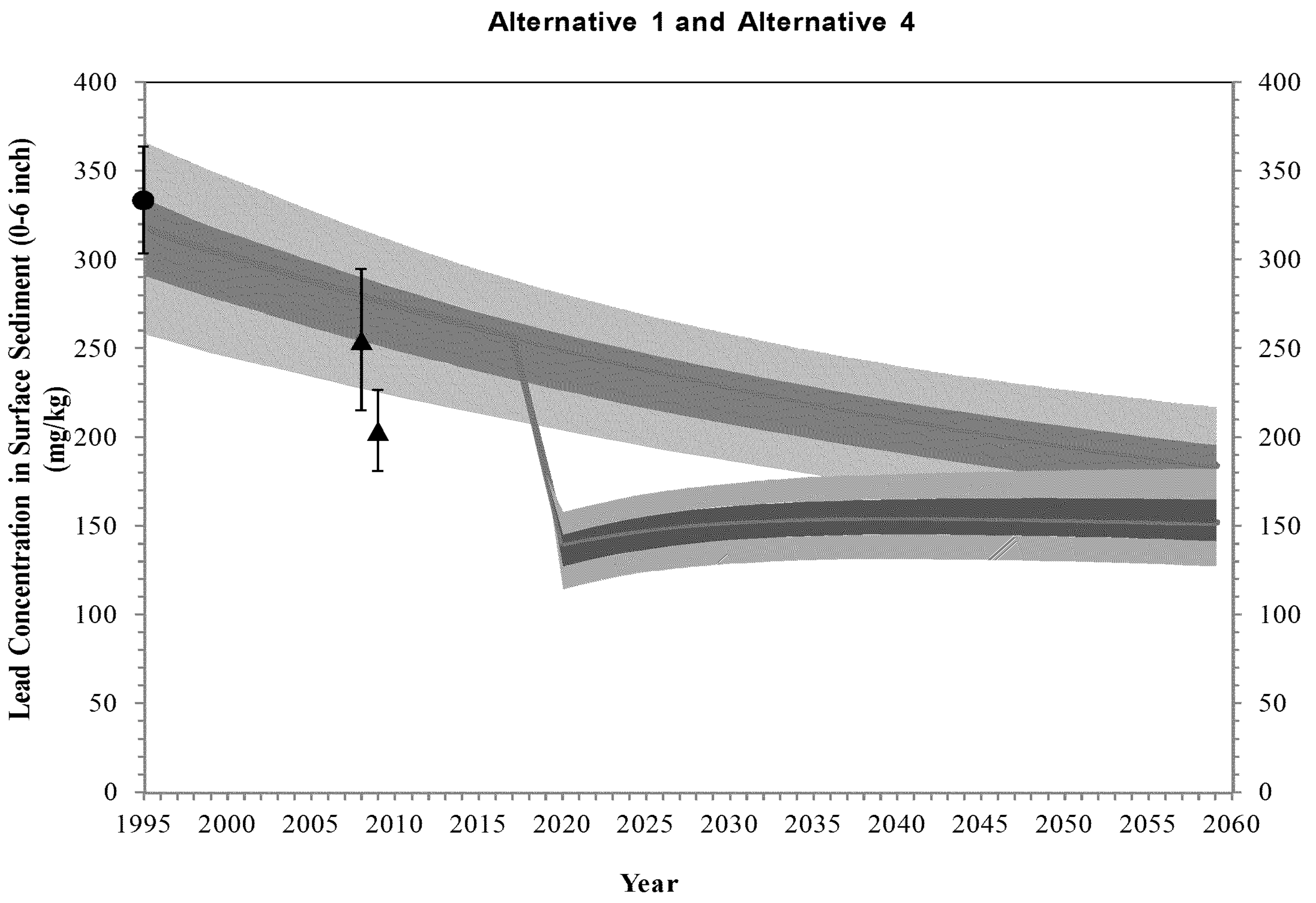
2014



Note

Best Estimate represents trajectory results using average input values for all parameters.

	Monte Carlo Trajectory Results for Lead Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3) *Lower Eight Miles of the Lower Passaic River*	Figure 5-13c 2014



Legend

Alternative 1

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 4

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

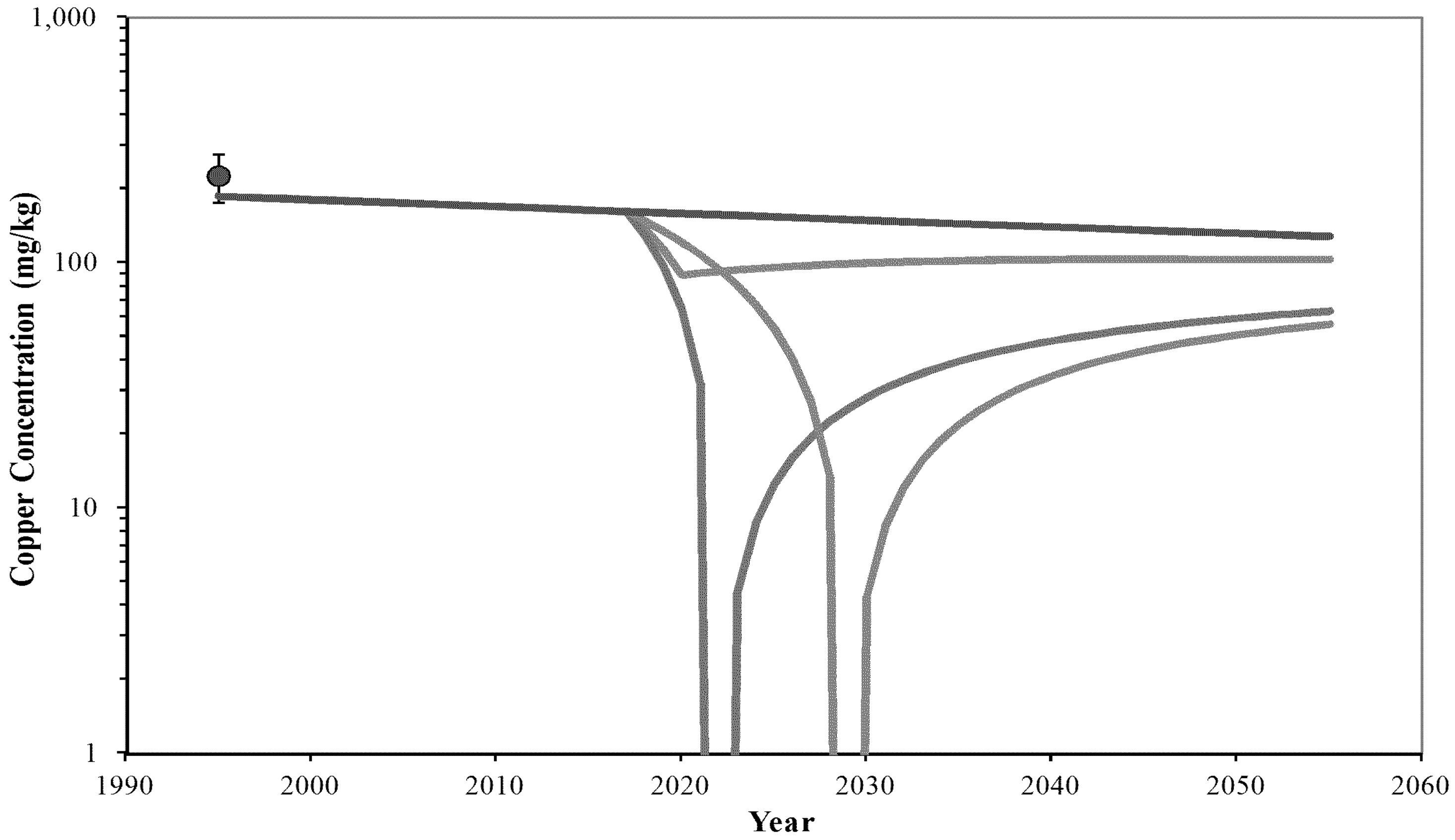
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Lead Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

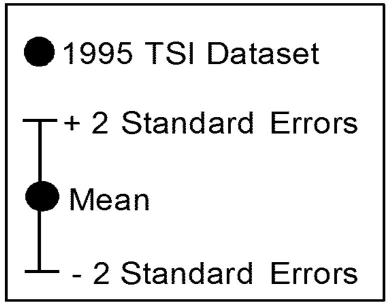
Lower Eight Miles of the Lower Passaic River

Figure 5-13d

2014



Legend



Note

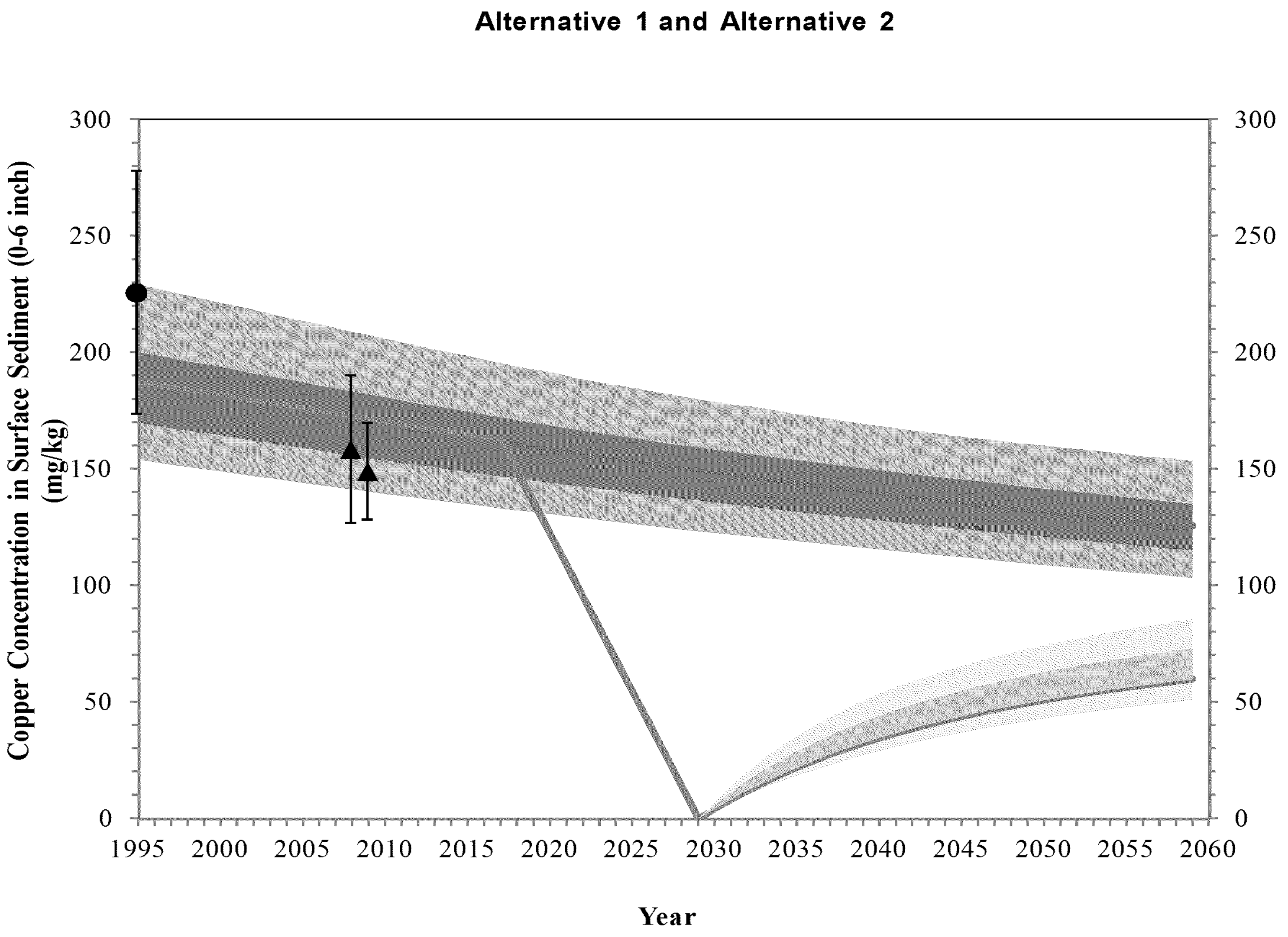
Best Estimate represents trajectory results using average input values for all parameters.

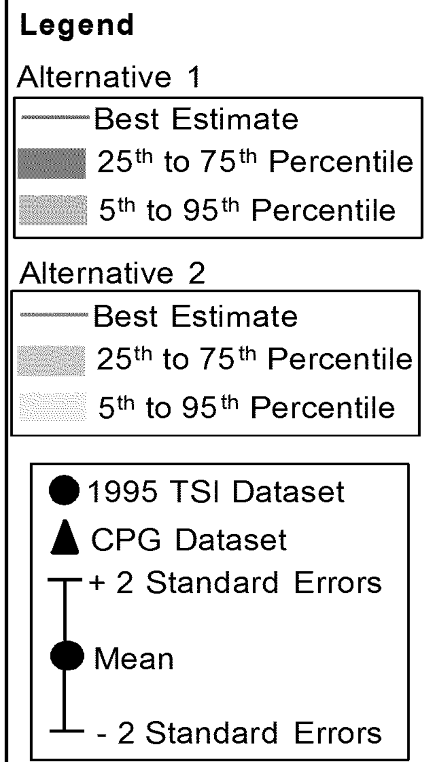
Copper Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-14a

2014





Note

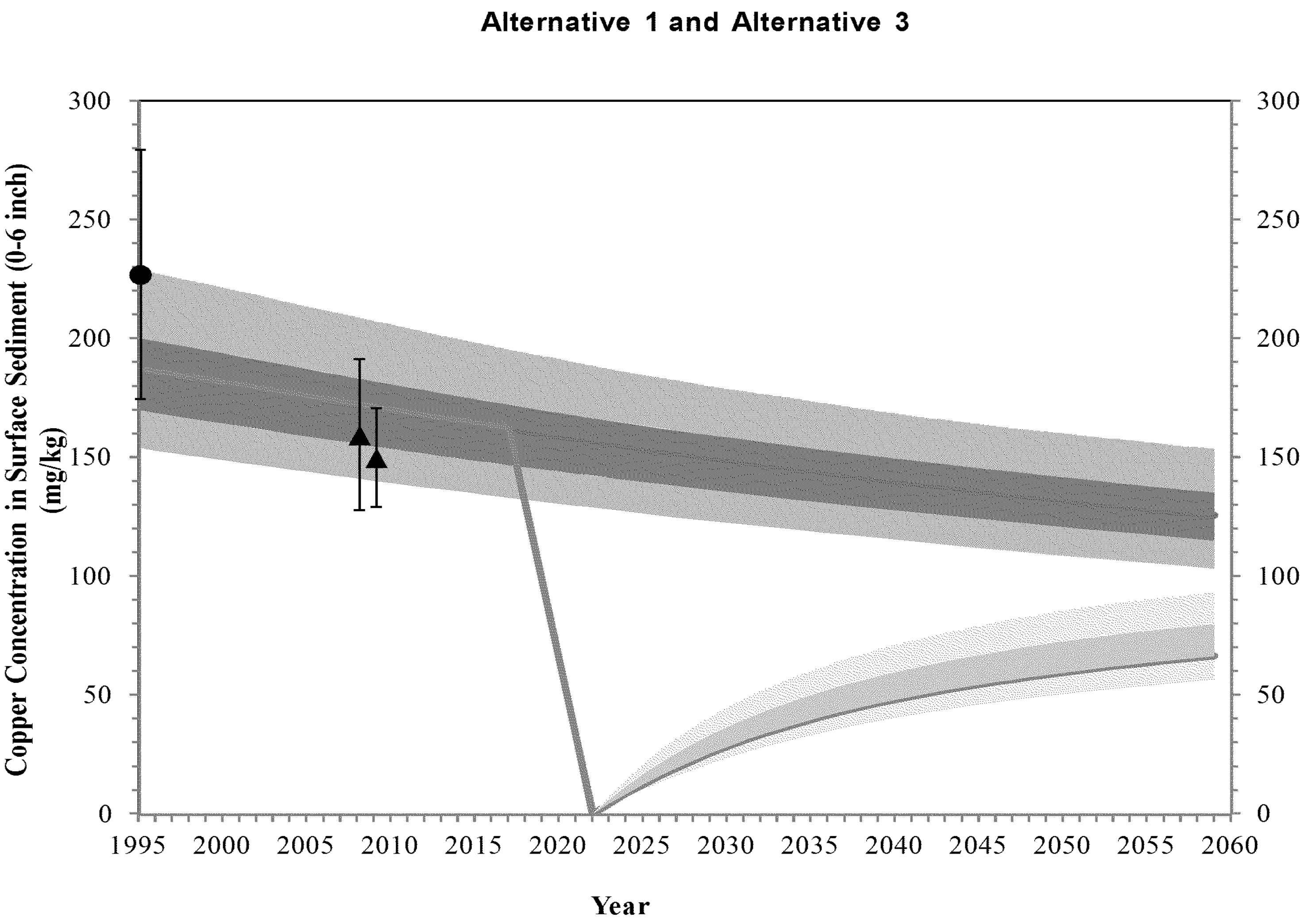
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Copper Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2)

Lower Eight Miles of the Lower Passaic River

Figure 5-14b

2014



Legend

Alternative 1

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 3

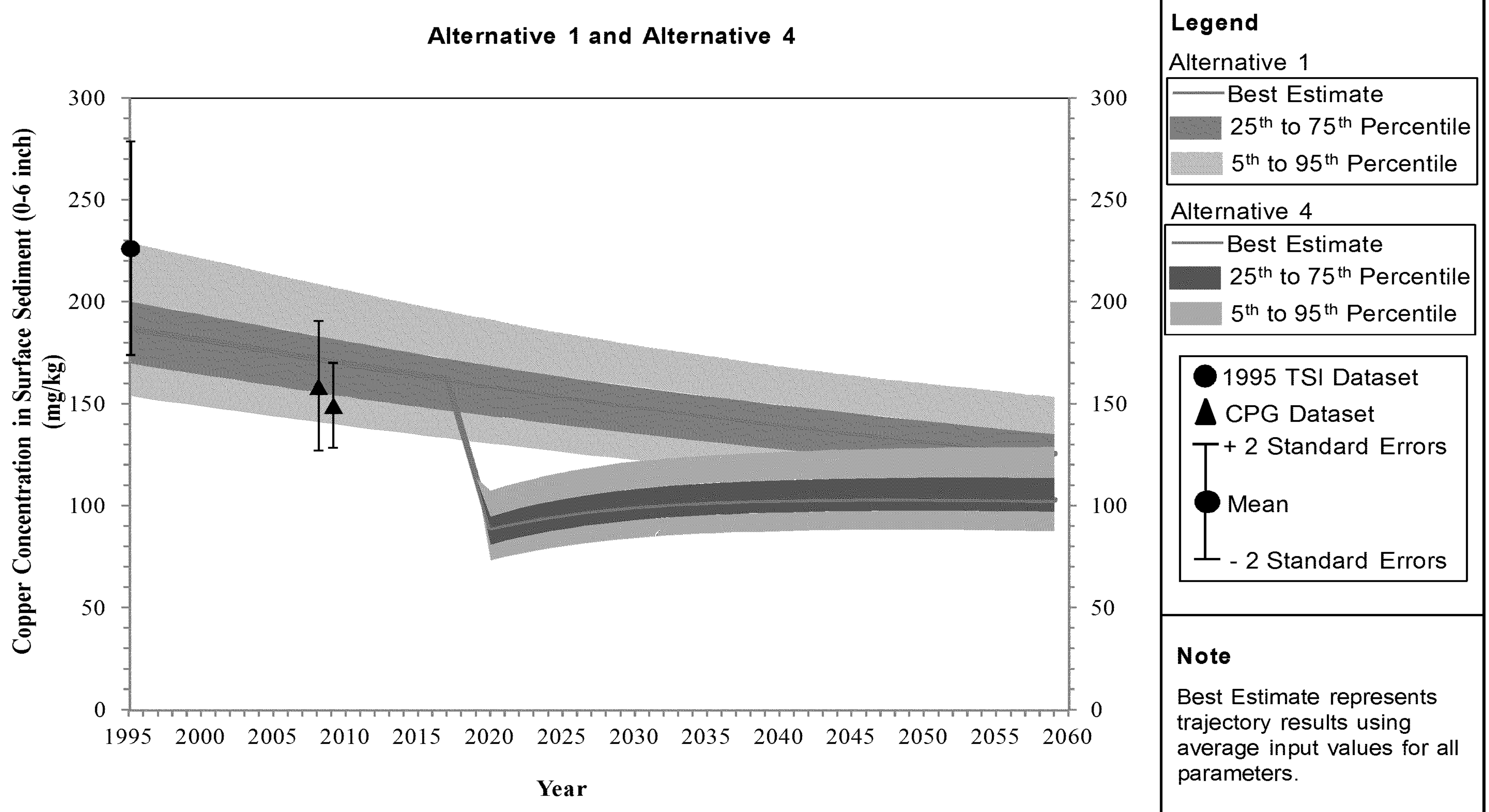
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- \+ 2 Standard Errors
- Mean
- \- 2 Standard Errors

Note

Best Estimate represents trajectory results using average input values for all parameters.

	Monte Carlo Trajectory Results for Copper Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3) *Lower Eight Miles of the Lower Passaic River*	Figure 5-14c 2014



Note

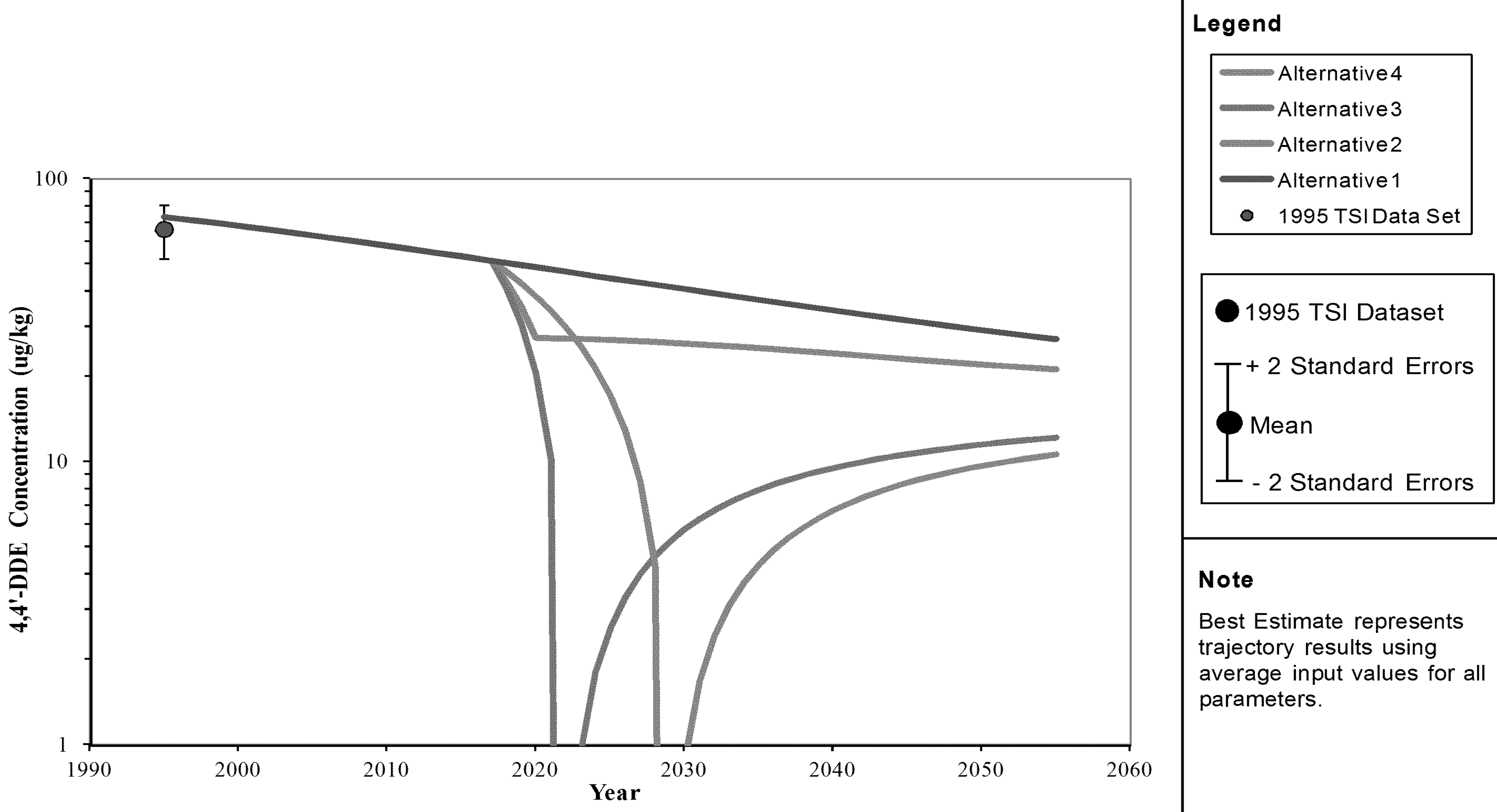
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Copper Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

Lower Eight Miles of the Lower Passaic River

Figure 5-14d

2014



Note

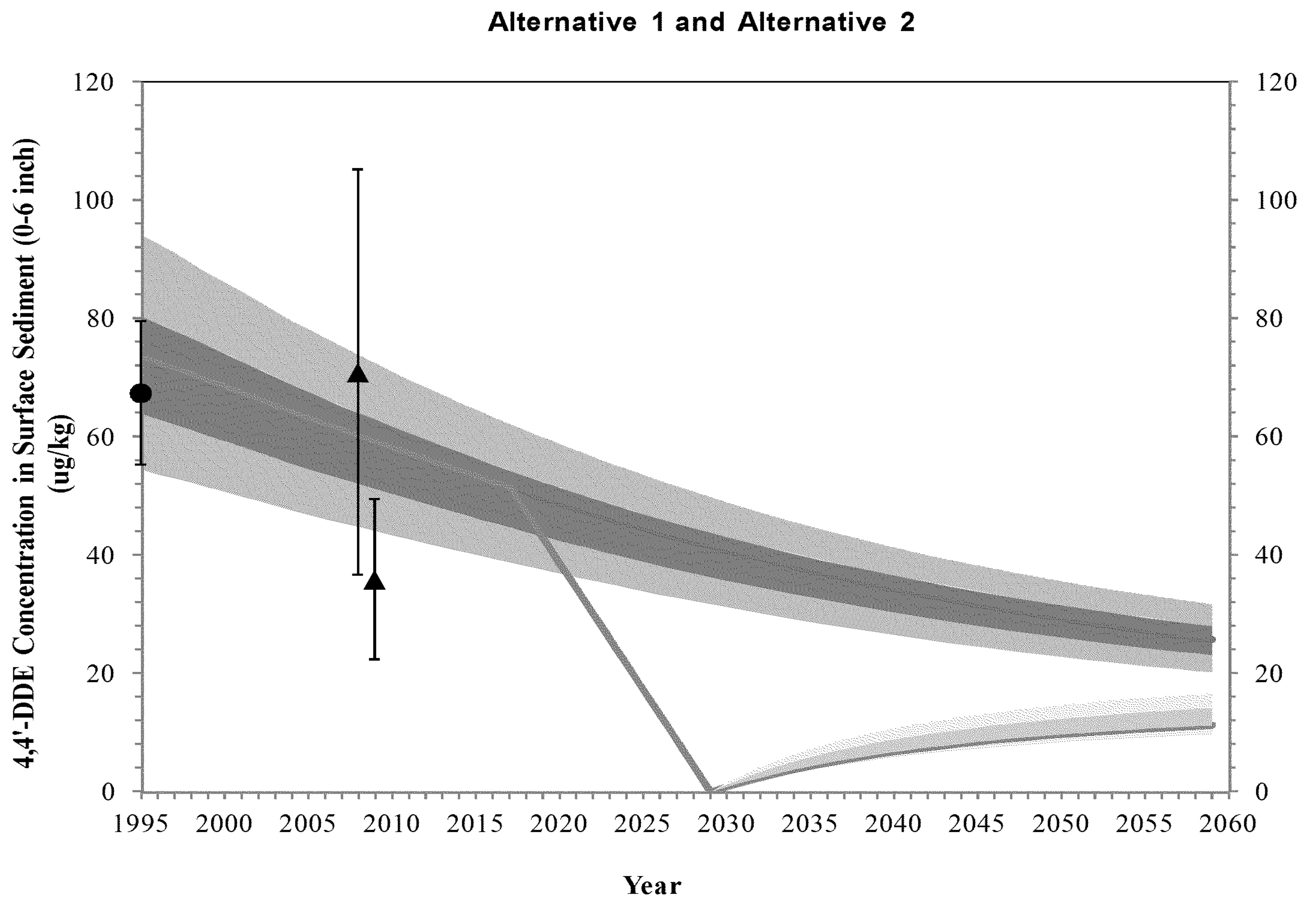
Best Estimate represents trajectory results using average input values for all parameters.

4,4'-DDE Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-15a

2014



Legend

Alternative 1
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 2
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

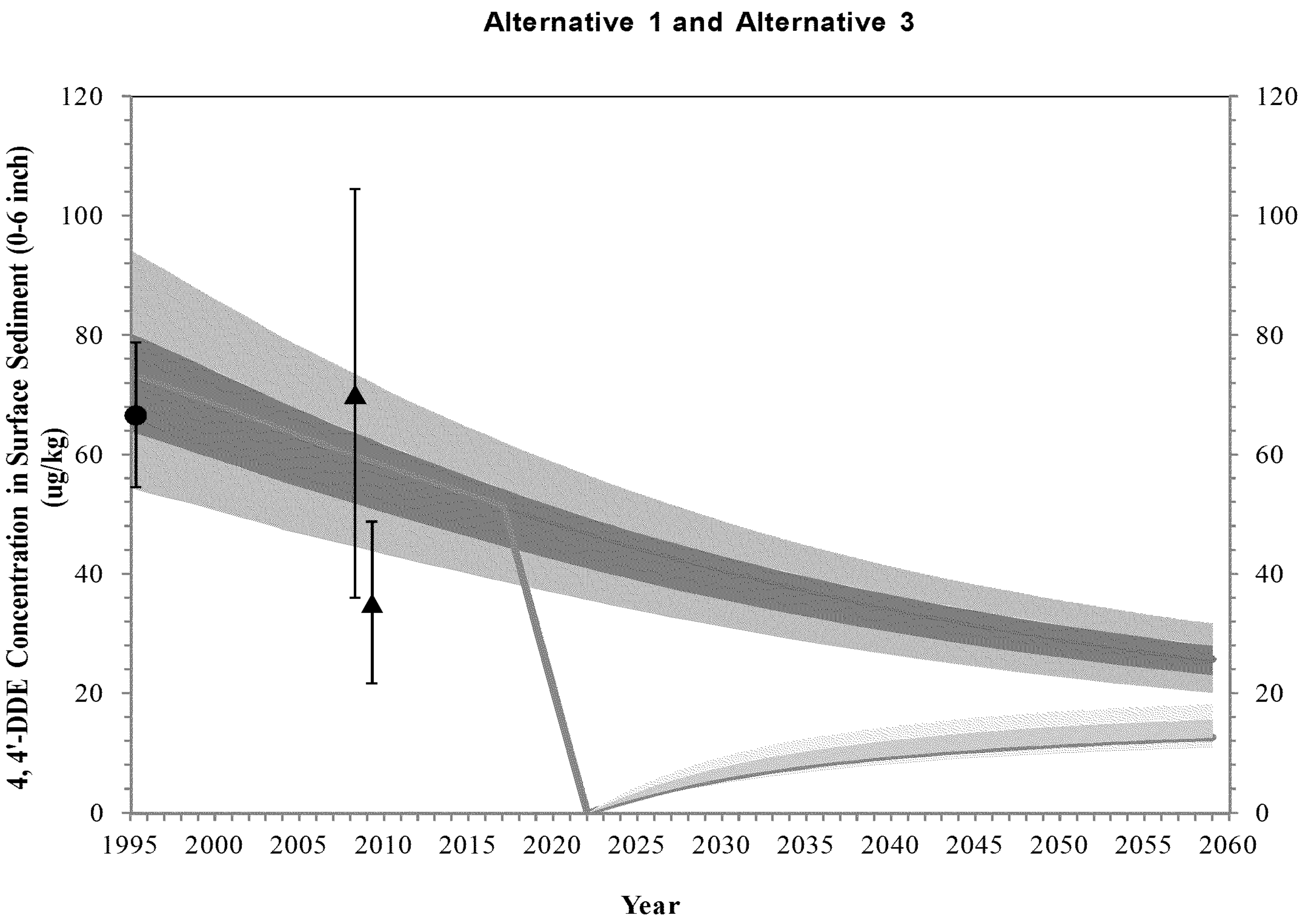
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for 4,4'-DDE Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2)

Lower Eight Miles of the Lower Passaic River

Figure 5-15b

2014



Legend

Alternative 1
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 3
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

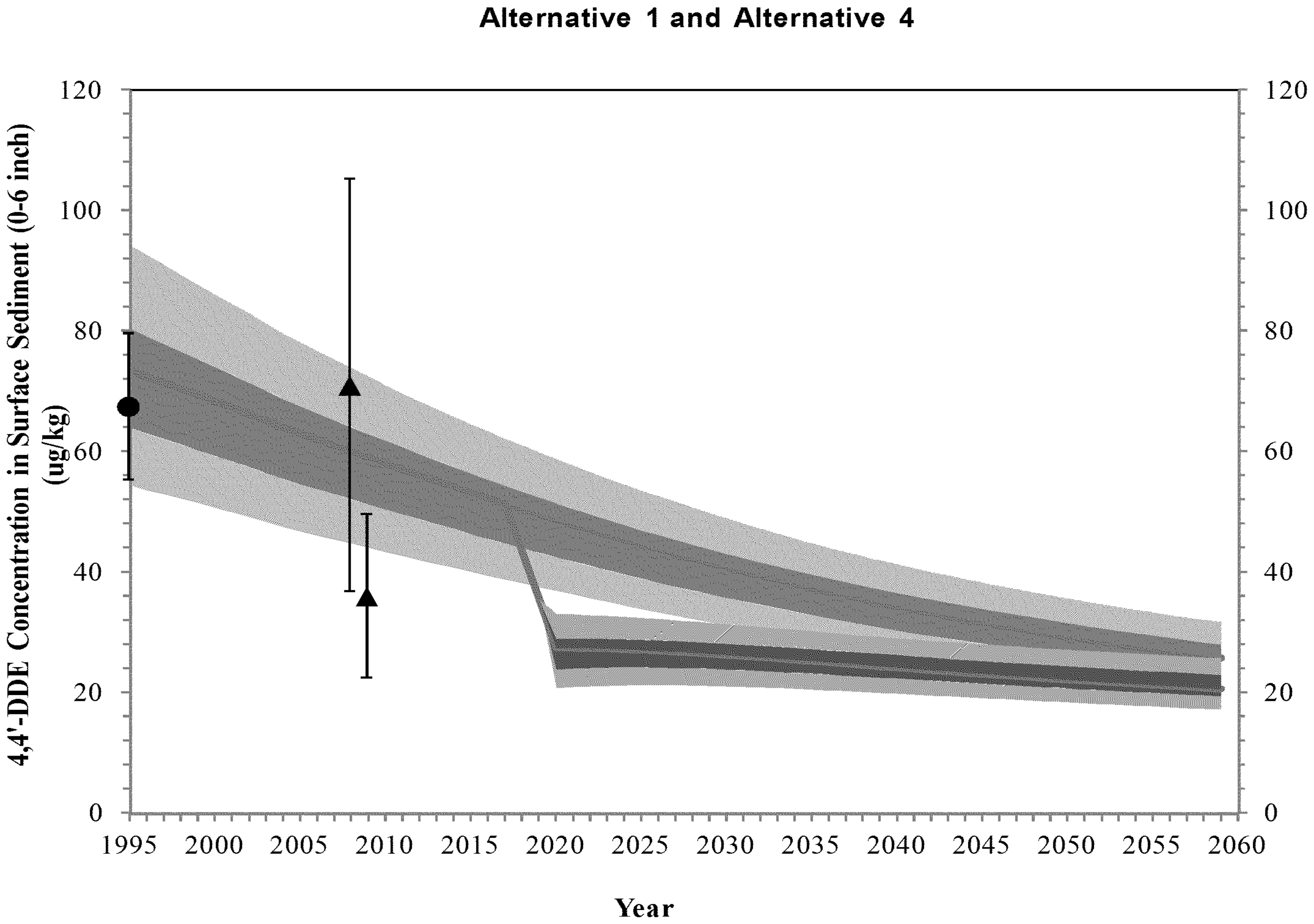
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for 4,4'-DDE Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3)

Lower Eight Miles of the Lower Passaic River

Figure 5-15c

2014



Legend

Alternative 1
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 4
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

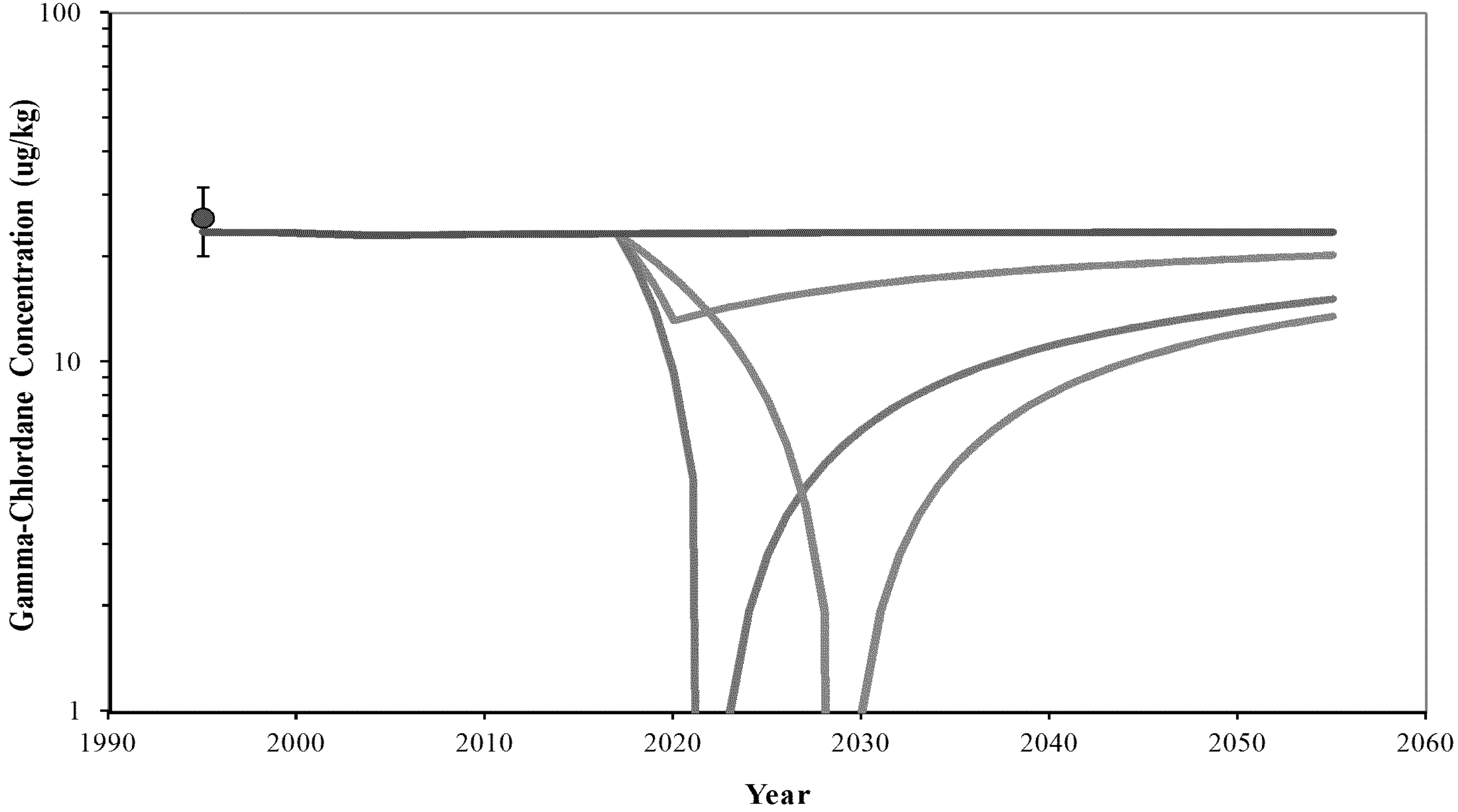
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for 4,4'-DDE Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

Lower Eight Miles of the Lower Passaic River

Figure 5-15d

2014



Legend

- Alternative 4
- Alternative 3
- Alternative 2
- Alternative 1
- 1995 TSI Data Set

1995 TSI Dataset

+ 2 Standard Errors

Mean

- 2 Standard Errors

Note

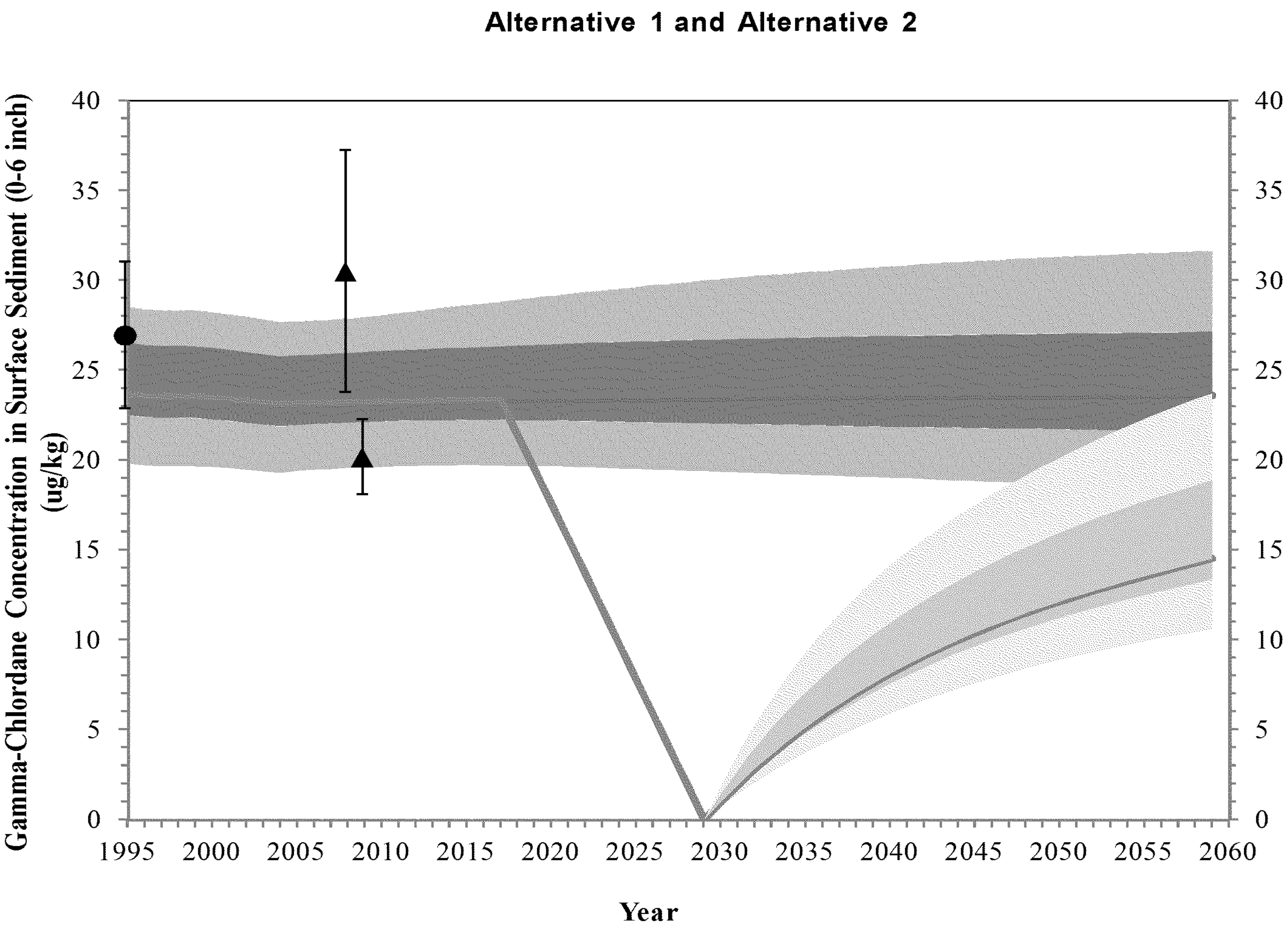
Best Estimate represents trajectory results using average input values for all parameters.

gamma-Chlordane Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-16a

2014



Legend

Alternative 1
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 2
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- \+ 2 Standard Errors
- Mean
- \- 2 Standard Errors

Note

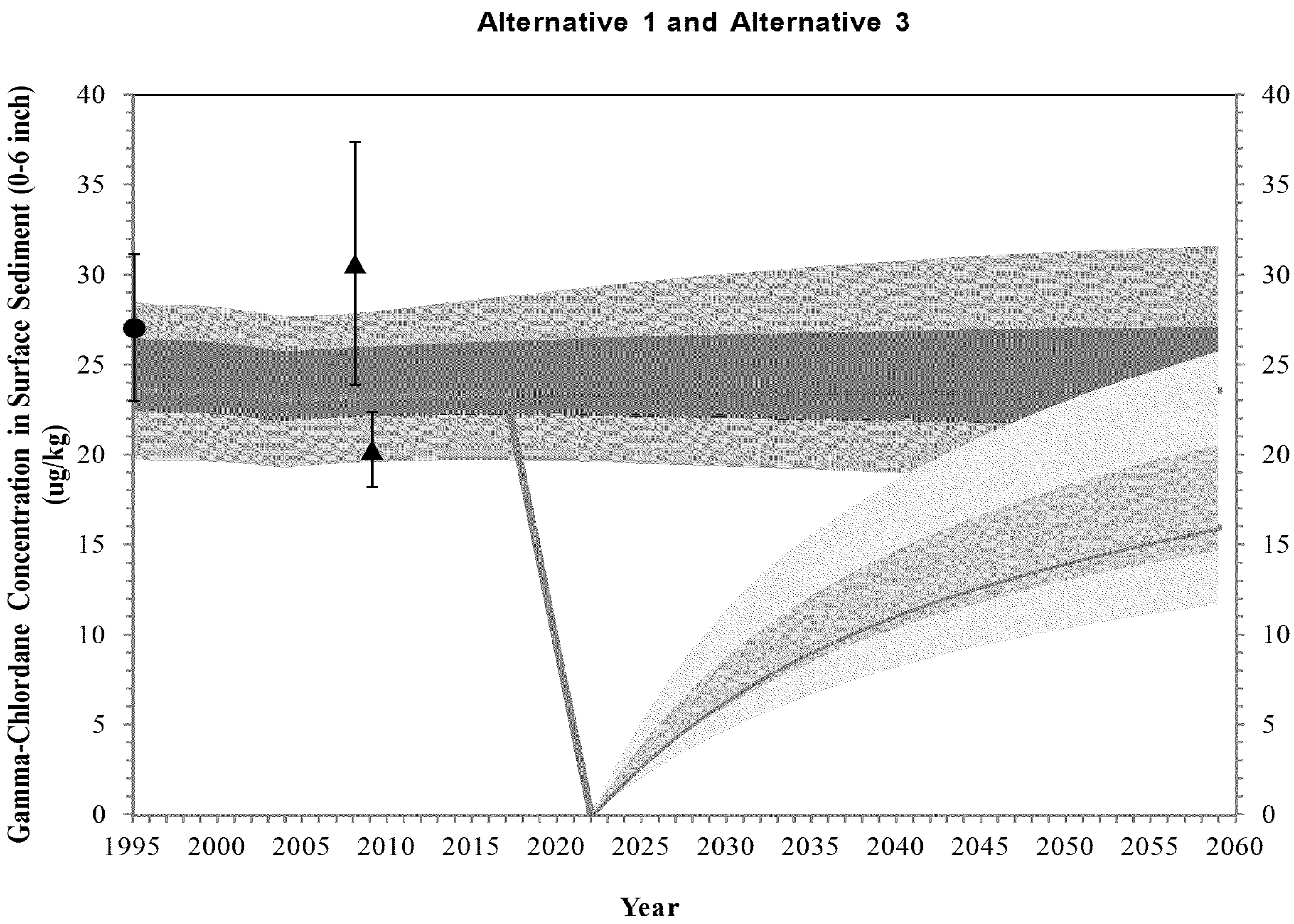
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for gamma-Chlordane Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2)

Lower Eight Miles of the Lower Passaic River

Figure 5-16b

2014



Legend

Alternative 1
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 3
- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

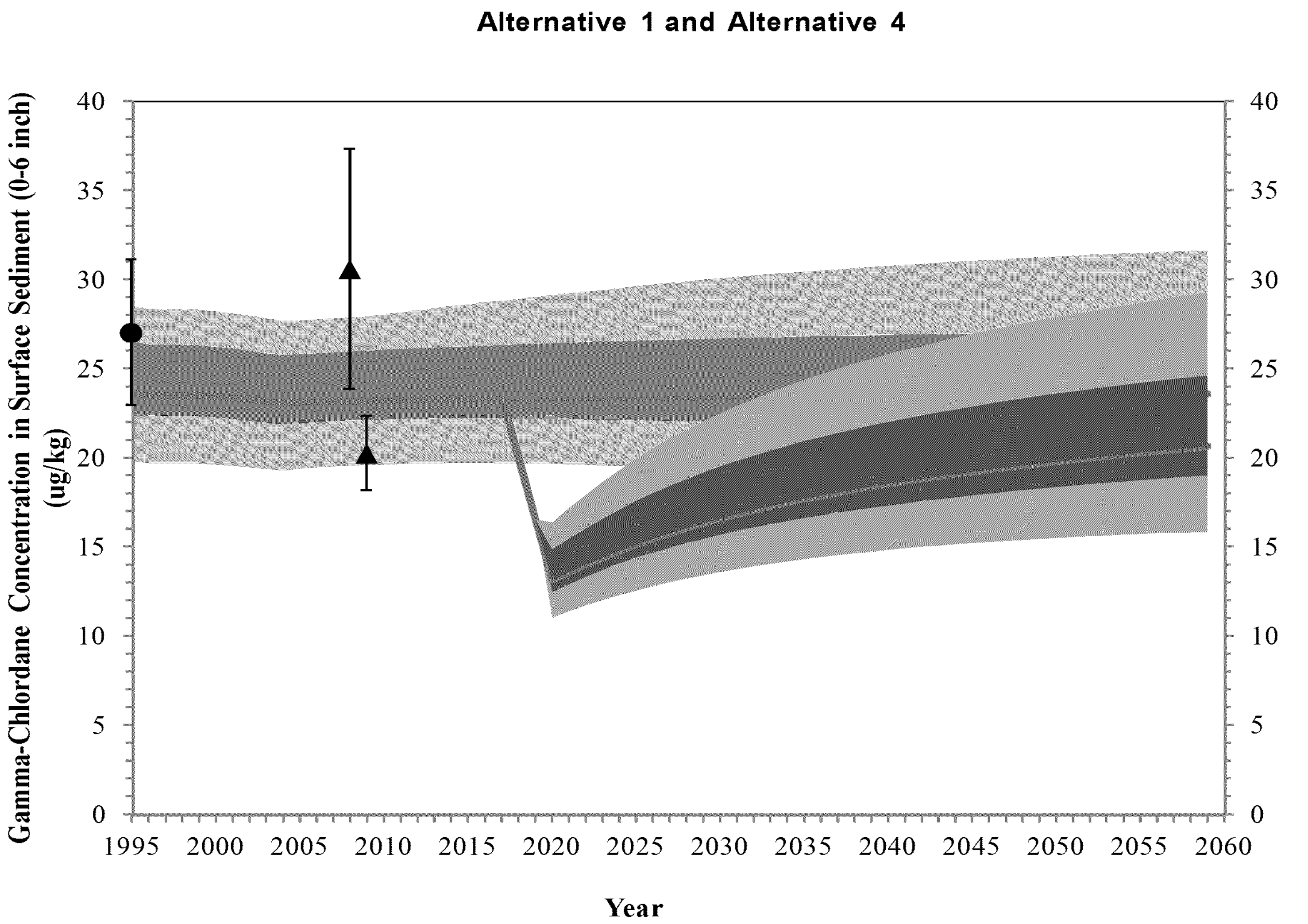
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for gamma-Chlordane Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3)

Lower Eight Miles of the Lower Passaic River

Figure 5-16c

2014



Legend

Alternative 1

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 4

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

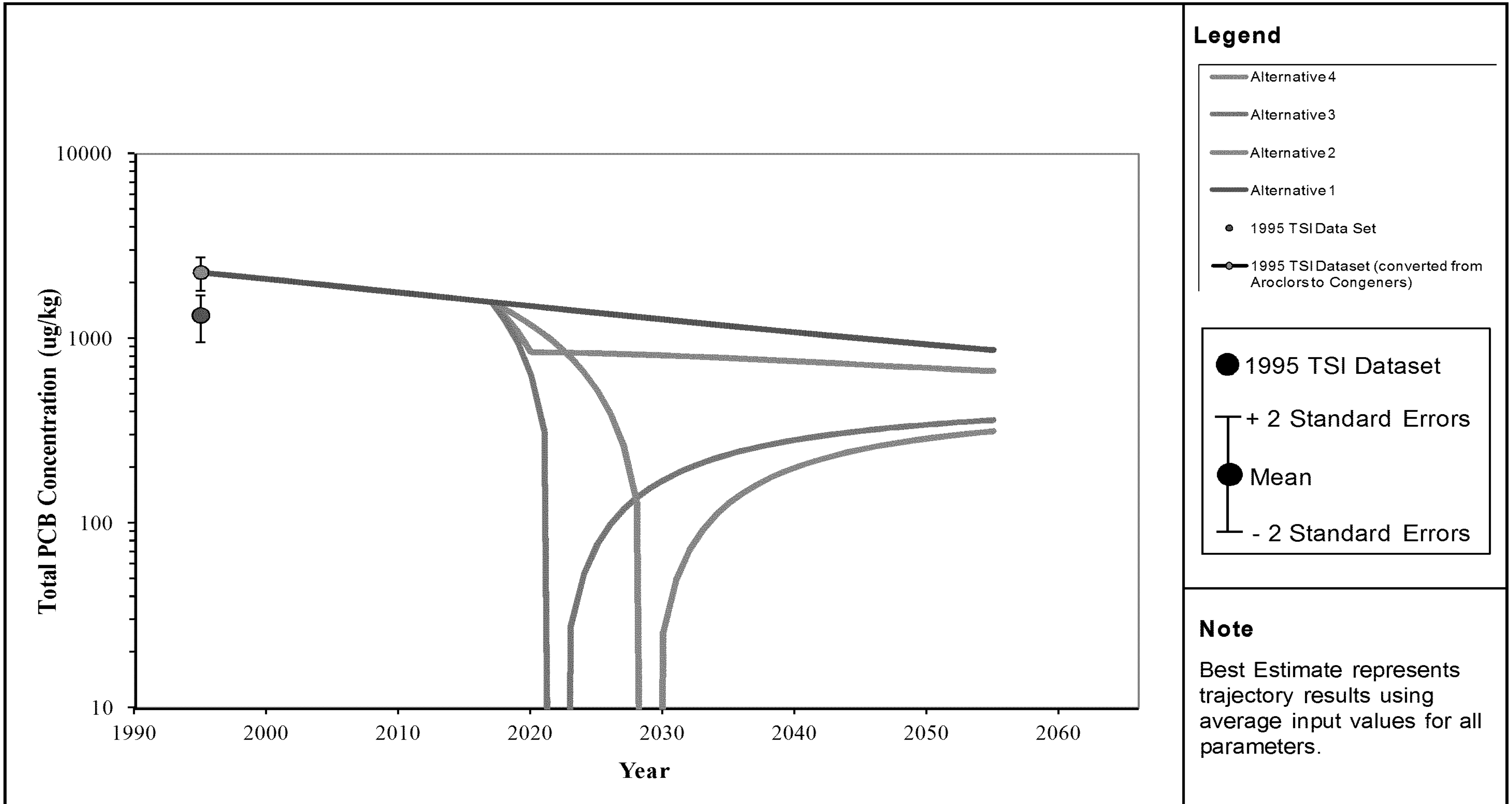
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for gamma-Chlordane Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

Lower Eight Miles of the Lower Passaic River

Figure 5-16d

2014



Note

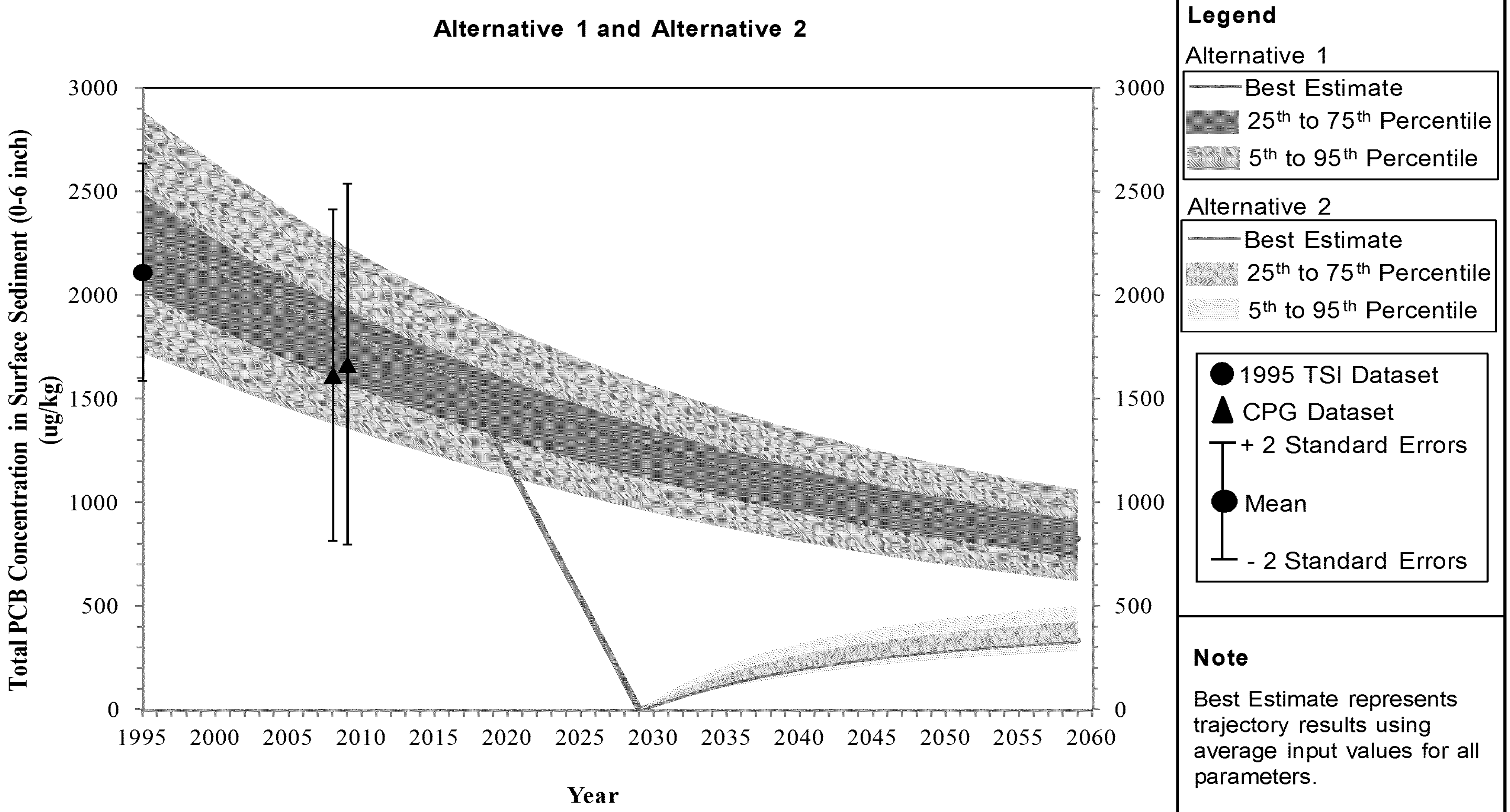
Best Estimate represents trajectory results using average input values for all parameters.

Total PCB Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-17a

2014



Note

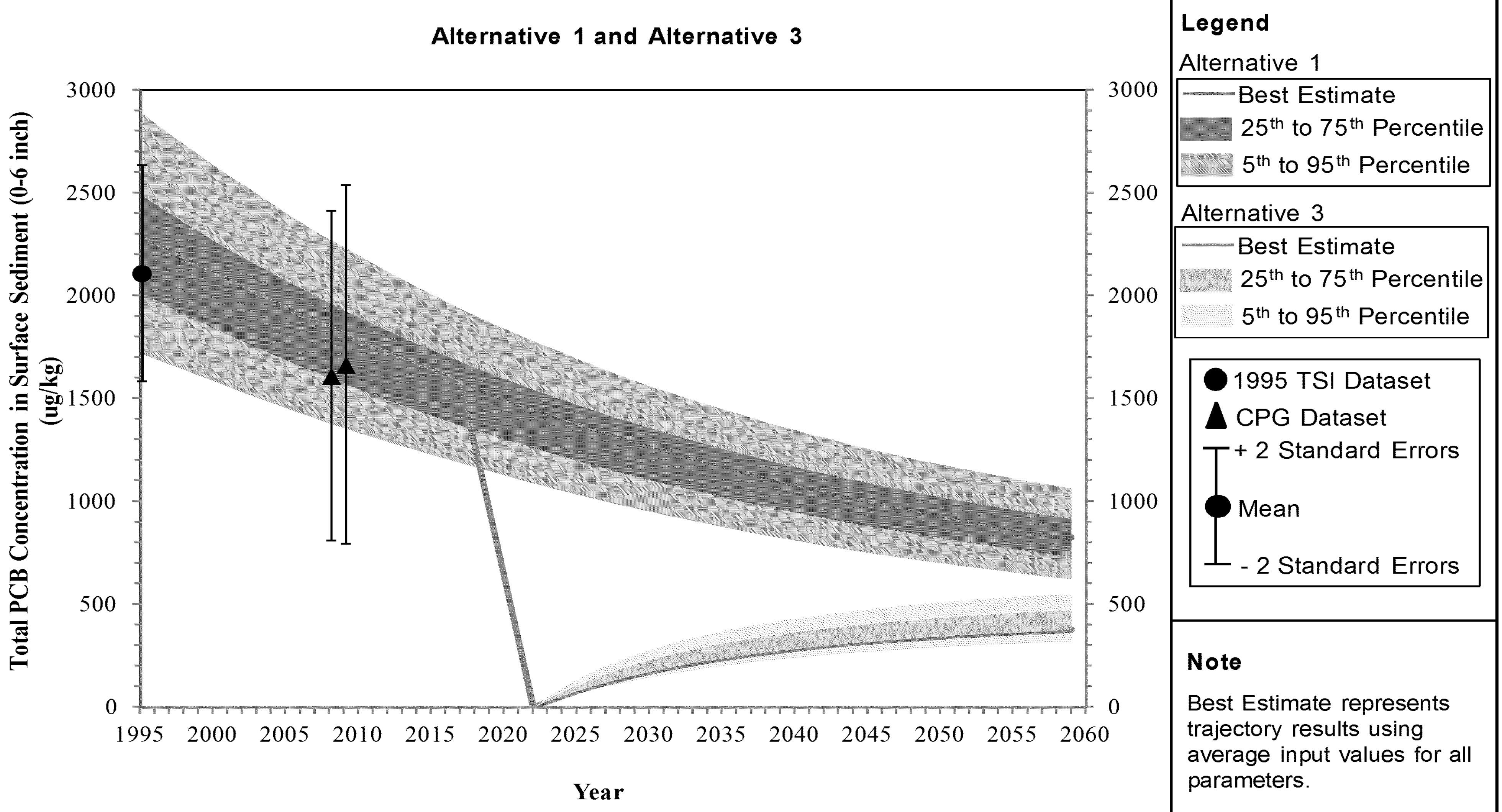
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Total PCB Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 2)

Lower Eight Miles of the Lower Passaic River

Figure 5-17b

2014



Note

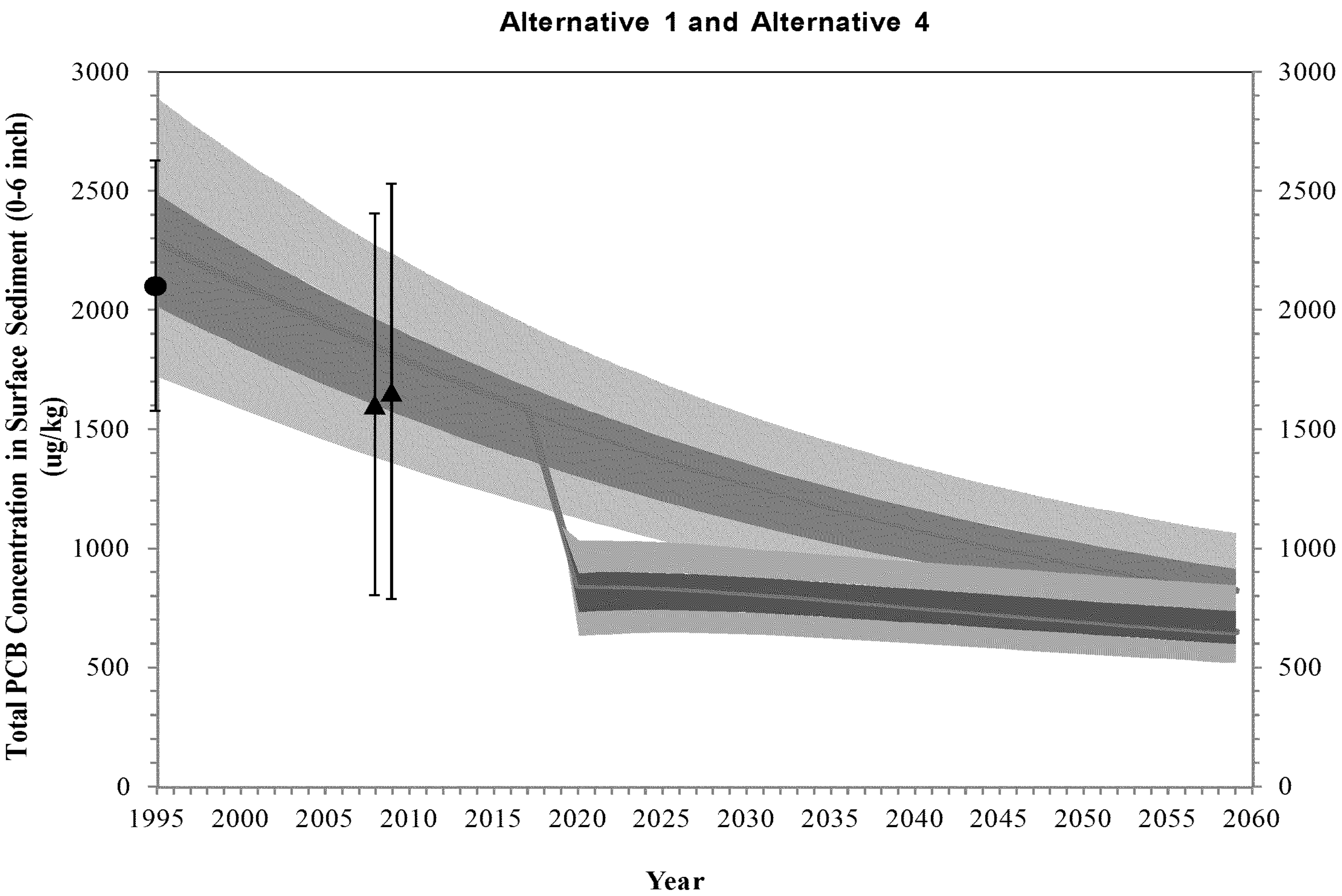
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Total PCB Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 3)

Lower Eight Miles of the Lower Passaic River

Figure 5-17c

2014



Legend

Alternative 1

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

Alternative 4

- Best Estimate
- 25th to 75th Percentile
- 5th to 95th Percentile

- 1995 TSI Dataset
- CPG Dataset
- + 2 Standard Errors
- Mean
- - 2 Standard Errors

Note

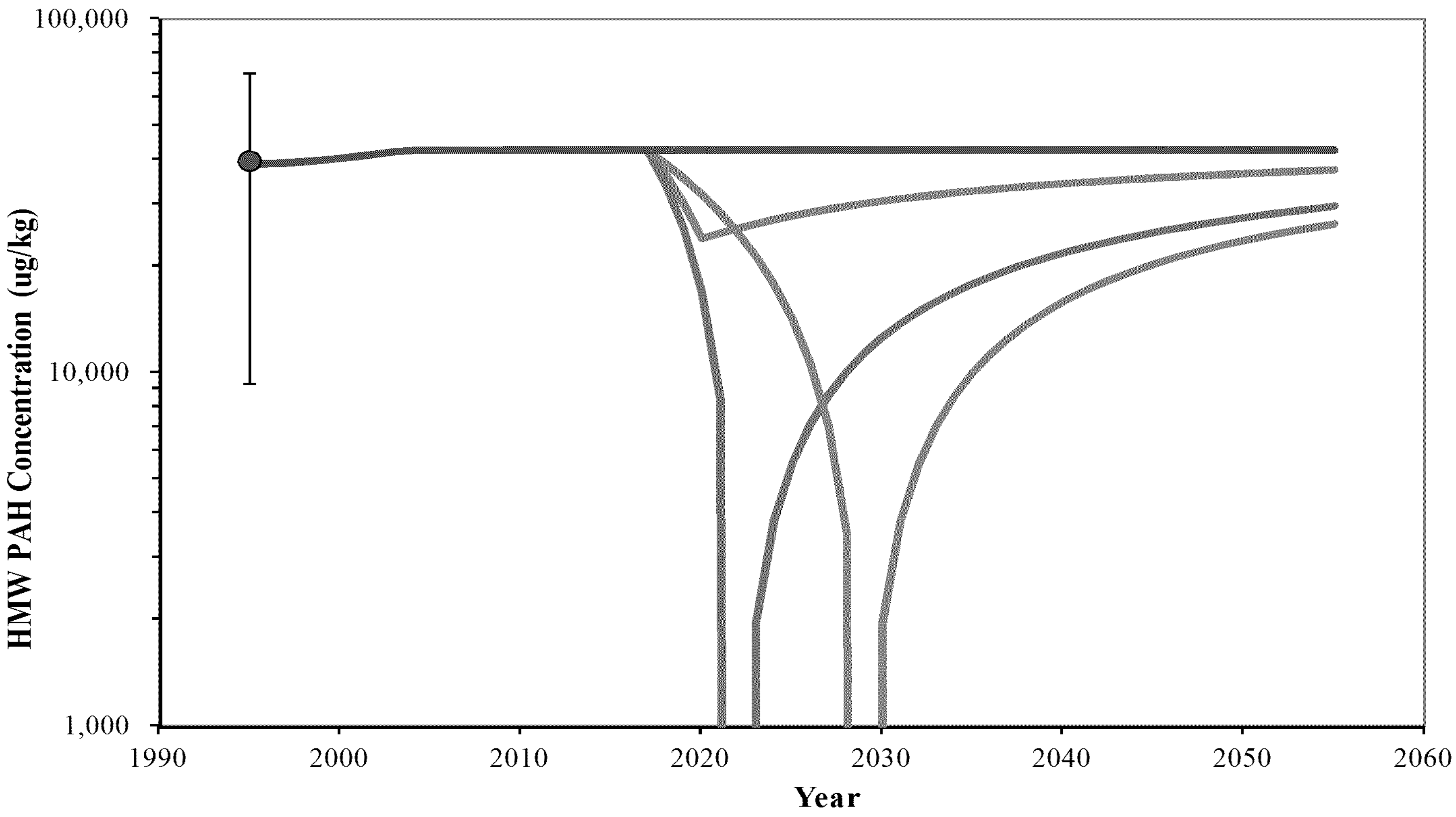
Best Estimate represents trajectory results using average input values for all parameters.

Monte Carlo Trajectory Results for Total PCB Concentration in 0-6 inch Surface Sediment (Alternative 1 and Alternative 4)

Lower Eight Miles of the Lower Passaic River

Figure 5-17d

2014



Legend

- Alternative 4
- Alternative 3
- Alternative 2
- Alternative 1
- 1995 TSI Data Set

1995 TSI Dataset

+ 2 Standard Errors

Mean

- 2 Standard Errors

Note

Best Estimate represents trajectory results using average input values for all parameters.

HMW PAH Best Estimates of Trajectories for 0-6 inch Biologically Active Layer

Lower Eight Miles of the Lower Passaic River

Figure 5-18

2014

ATTACHMENTS

ATTACHMENT A

MONTE CARLO METHODOLOGY FOR UNCERTAINTY ANALYSIS ON THE EMB MODEL AND FORECAST TRAJECTORIES

Attachment A: Monte Carlo Methodology for Uncertainty Analysis on EMB Model and Forecasts Trajectory.

1.0 Introduction

Environmental systems generally have several sources of uncertainties, and these uncertainties are not only due to a lack of proper measurements, but also due to the randomness inherent in real ecosystems. Incorporating these uncertainties into the modeling process could potentially result in providing useful information that can aid in decision-making.

The EMB model best estimate scenario assumed average values for all model inputs in determining the solids contribution, fate and transport of chemicals, as well as the forecast of future surface sediment concentrations under various remedial scenarios. To incorporate uncertainties in model parameters, a Monte Carlo[1] sampling approach was used to develop 10,000 iterations of each input. These 10,000 inputs were optimized in the EMB model and the optimized results were carried through the trajectory forecast calculations. A combination Microsoft Excel® Solver and the Crystal Ball® 7 (Decisioneering, Denver, CO, USA) add-on for Microsoft Excel® (a tool typically used for solving optimization problems), was used to perform this analysis. The objective of the uncertainty analysis was to provide an insight into the level of confidence in the model estimates for the best estimate scenario. This attachment presents the detailed methodology for the Monte Carlo analysis for the EMB model and Trajectory forecasts.

2.0 Methodology

The following stages were involved in the uncertainty analysis of the solids and contaminant mass balances, and contaminant forecasts presented in the Appendix C: (a) characterization of uncertainties in EMB model input chemical profiles, (b) estimation of the uncertainty in EMB model optimized outputs resulting from the uncertainty in chemical profiles, and (c) characterization of the uncertainties in model forecast resulting from uncertainties in the input profiles, EMB model outputs of solids contribution, decay of excess contaminant concentrations (lambda), and depth of resuspension reservoir/mixed layer (uncertainty propagation). A schematic diagram illustrating the Monte Carlo methodology is given in Figure A-1 and detailed description is presented below.

[1] Monte Carlo simulation is categorized as a sampling method in which the trails or realizations are randomly generated from probability distributions to simulate the process of sampling from an actual population.

2.1 Uncertainties in EMB Model chemical input profiles

Thirteen chemicals (copper, chromium, mercury, lead, gamma-Chlordane, 4,4'-DDE, 2,3,7,8 TCDD, Total TCDD, Total PCB, benzo(a)pyrene, fluoranthene, iron, and TOC) were optimized in the EMB model to determine the solids balance. The uncertainties in the concentrations of these 13 chemicals for the external sources, and the resuspension source were defined by parametric and non-parametric statistics, respectively. These are described below.

2.1.1 External Sources and Receptor Profiles

The observed concentrations for the 13 chemicals for the external sources (Upper Passaic River, Newark Bay, Saddle River, Second River/SWO, Third River, and CSOs) were generally normally distributed. For each external source and the receptor, a bounded normal distribution defined by the mean, standard deviation, minimum, and maximum of each chemical was used to perform Monte Carlo simulation in Crystal Ball® 7. In performing these Monte Carlo simulations, it was important to maintain the relationship amongst the variables. Therefore, for each source, the correlation matrix was also specified in Crystal Ball® 7 to ensure that the 10,000 iterations of chemical profile represented the variability, inter-dependencies, and uncertainty for each external source and the receptor. Figure A-2a though A-2g presents the statistical distribution s of chemical concentrations for the 13 chemicals optimized in the EMB model, for the external sources and the receptor.

2.1.2 Resuspension Source Profiles

The chemical profiles for the resuspension source were generated based on the TSI 1995 observations. The concentrations of each chemical in this data were neither normal nor log-normal distributed. None of the complex parametric distributions in Crystal Ball® 7 could adequately fit the data set. Therefore, to create the 10,000 iterations of concentrations for the resuspension source profile, a non-parametric simulation method called a bootstrap [2] was used.

The basic bootstrap approach uses Monte Carlo sampling to generate an empirical estimate of the sampling distribution of interest. In the bootstrap method, the 1995 data set was treated as the population and a Monte Carlo-style procedure was conducted on it to 10,000 iterations of the mean of the 13 chemicals optimized. This was done as follows:

[2] Bootstrap is a powerful Monte Carlo method that re-samples the original sample set with replacement to generate a distribution of sample's statistics. It is a non-parametric method.

1. The original sample locations, totaling 92 from the 1995 TSI data set were assumed to define the population of data set in surface sediments for resuspension. Note that in performing this analysis, TSI Location 246 was removed from the data set because the PAH concentrations at this location were not representative of PAH values generally reported in the 1995 TSI data set.

2. The original locations were re-sampled with replacement to generate a bootstrap sample of size 91. This creates a bootstrap data set of the same size as the original, excluding Location 246. By re-sampling the locations rather than each chemical independently, the correlations amongst the chemicals were maintained. Note that this bootstrap sample set may include some sample numbers in the original sample several times, and at the same time other sample numbers may be excluded.

3. Using the chemical concentrations for the locations selected in the 91 bootstrap samples, the average concentration for each chemical was calculated.

4. Steps 2 and 3 were repeated 10,000 times to generate the empirical distribution of the resuspension source profile (Figure A-2h).

The 10,000 average concentrations generated for each chemical via bootstrap for resuspension were used along with the 10,000 iterations for the external sources and receptor to represent the uncertainty in the inputs for EMB model optimization.

2.2 Estimation of uncertainty in EMB Model Output

A Microsoft Excel® macro[3], which calls the SOLVER routine, was developed to perform the EMB model optimization with the aim of determining the relative solids contributions from the various sources and the mass balance for the chemicals optimized. The macro was used to solve the 10,000 optimizations using the 10,000 iterations of the sources and receptor generated by the Monte Carlo simulation. The results of the optimization run were used to understand the uncertainty in the relative source contributions and chemical mass balance for the Lower Passaic River. The 10,000 EMB model optimized results were also used as input to the trajectory forecast calculations.

[3] A Microsoft Excel® macro is a set of instructions written in Visual Basic programming language for Application that can be triggered by a keyboard shortcut, toolbar button or an icon in a spreadsheet. Macros are used to eliminate the need to repeat the steps of common tasks over and over.

2.3 Uncertainties in Trajectory Forecast

Uncertainties in forecasted chemical concentrations were defined by the results of 10,000 iterations of forecasted values. The chemicals forecasted included: 2,3,7,8-TCDD, mercury, copper, lead, 4,4'-DDE, Total PCB, and gamma-Chlordane. Four remedial alternatives were considered including: No Action (Alternative 1), Deep Dredging with Backfill (Alternative 2), Capping with Dredging for Flooding and Navigation (Alternative 3), and Focused Capping with Dredging for Flooding (Alternative 4). Complete descriptions of these alternatives are provided in FFS Chapter 4 and the assumptions made in the trajectories are given in Appendix C. Forecasting the future concentrations of chemicals under the various remedial scenarios required inputs of (i) chemical concentrations, (ii) solids contributions for the various sources determined by the EMB model optimization, (iii) decay of excess contaminant concentrations (lambda; λ), net sedimentation rate, and (iv) the depth of the sediment mixed layer. Uncertainties in these inputs were defined as follows:

1. Uncertainties in the chemical concentrations were defined by the 10,000 iterations used as inputs to the EMB model optimizations (Figure A-2). For each forecast calculation, the source and receptor profiles were represented by the Monte Carlo generated values as described in Section 2.1 above.

2. Uncertainties in solids contribution from the various sources were obtained from the uncertainty in the solids contributions determined by the EMB model optimization results. This was implemented by using the 10,000 solids contribution results from the EMB model.

3. Uncertainties in decay of excess sediment contamination were defined by the regression between the natural logarithm of the excess concentrations versus time (see Figure C-5-1 to C-5-10 in Appendix C). Using the slope (λ), standard error, and confidence bounds from the regressions, 10,000 iterations of λ were simulated using Monte Carlo sampling from bounded normal distributions (Figure A-3). Note: □□ □□□□□□ = ln (0.5)/□□ □

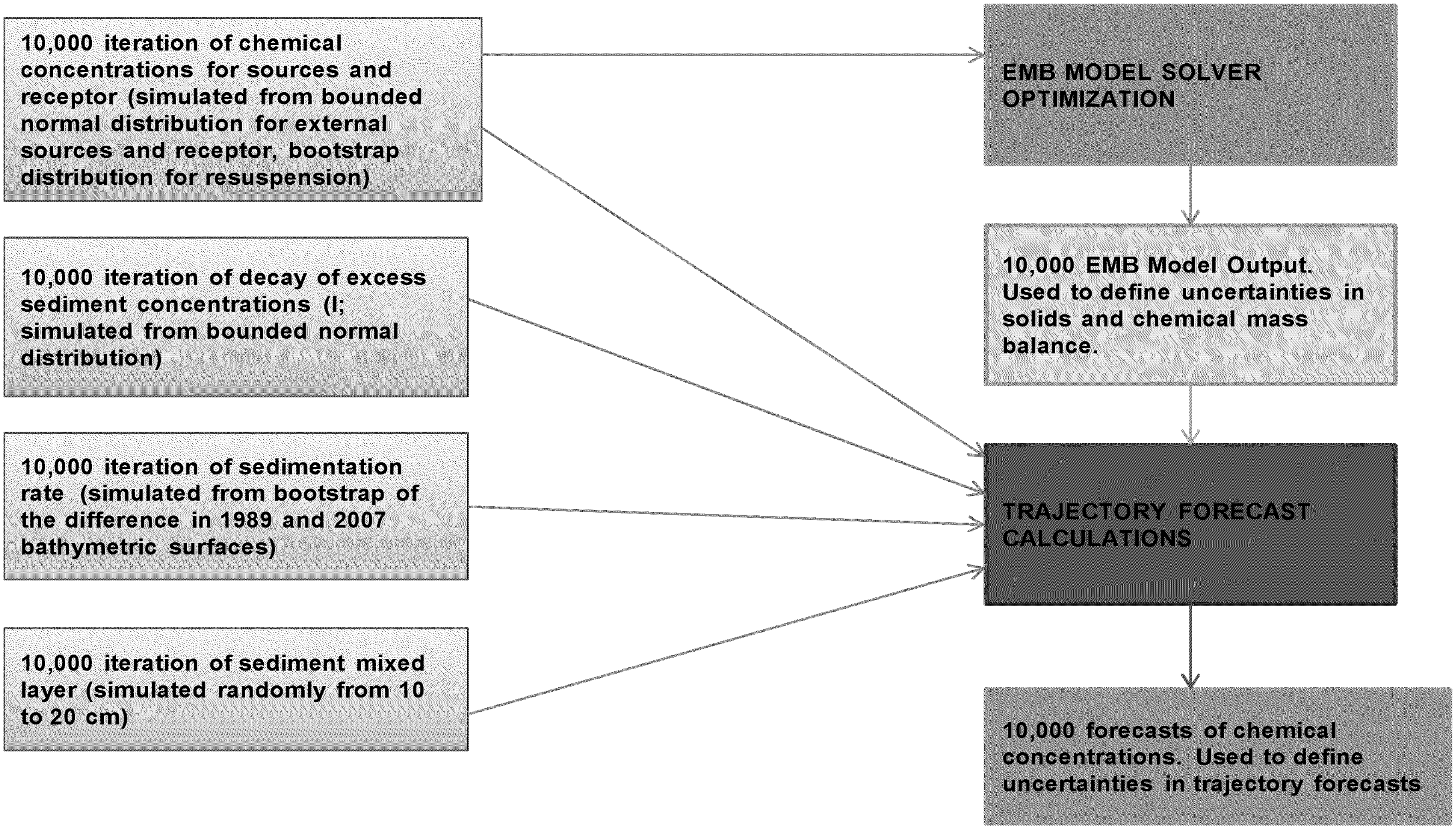
4. Uncertainties in the sedimentation rates were generated by bootstrap analysis of the differences between the 1989 and 2007 bathymetric surfaces (Figure A-4).

5. The uncertainties in depth of the sediment mixed layer were generated by 10,000 random numbers between 10 cm to 20 cm in Microsoft Excel®. Note that Microsoft Excel®'s random number generates uniform distributions of the parameter of interest (Figure A-5).

The Microsoft Excel® spreadsheets designed to perform forecast calculations using the best estimate for all inputs were modified to perform the calculations for the 10,000 iterations through a macro. For each iteration, the macro reads the input values of chemical concentrations, λ, sediment deposition rate and mixed layer depth, updates the forecast spreadsheet with these values, and then saves the results of the forecast calculation for all the remedial scenarios.

3.0 Results

Uncertainties in the EMB model solution and trajectory forecasts were defined by the confidence interval (5th and 95th percentiles) of the 10,000 optimized solutions. All the results are presented and discussed in Appendix C.

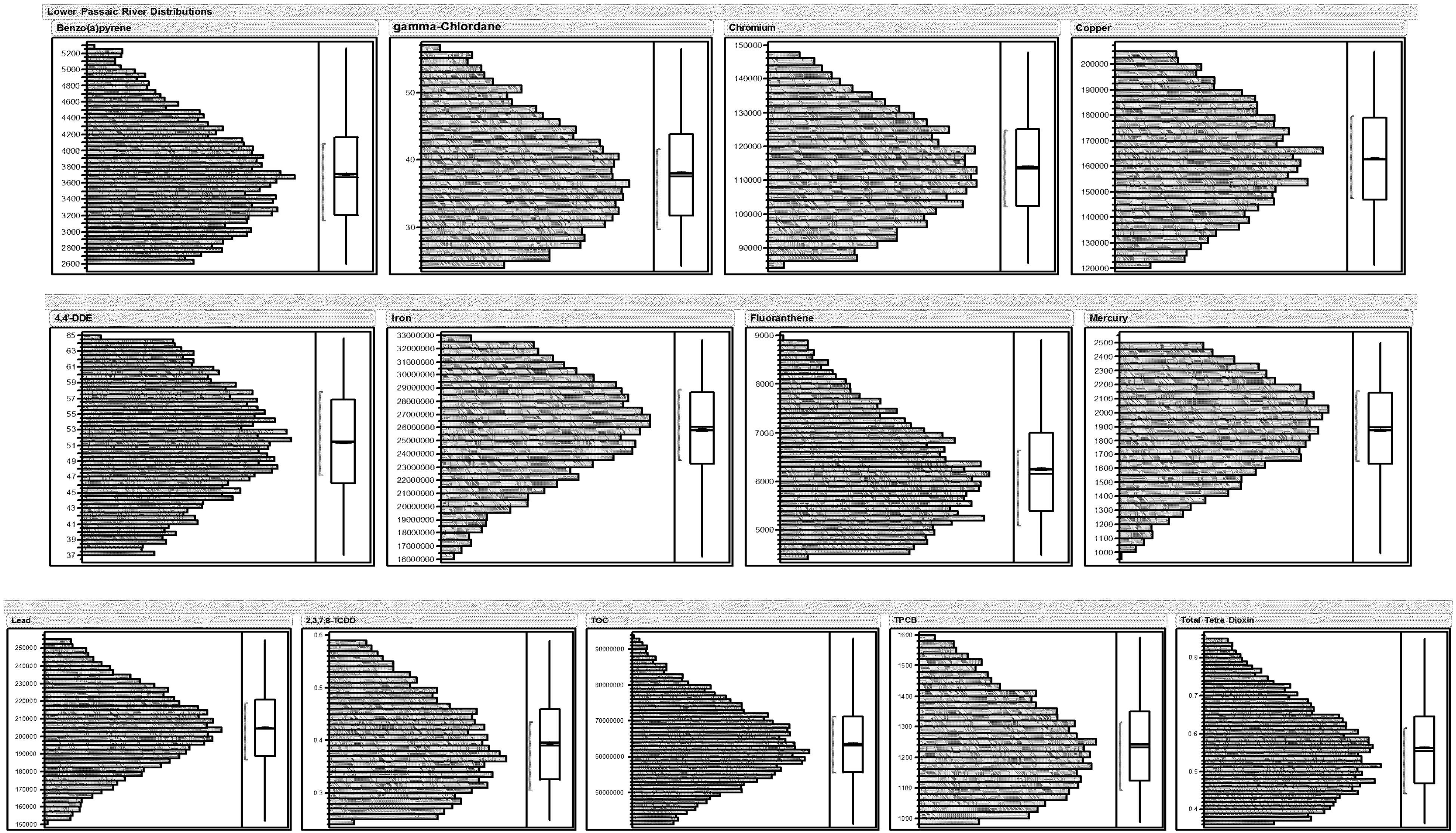


Schematic Diagram of Monte Carlo Methodology for Uncertainty Analysis on EMB Model and Trajectory Forecasts

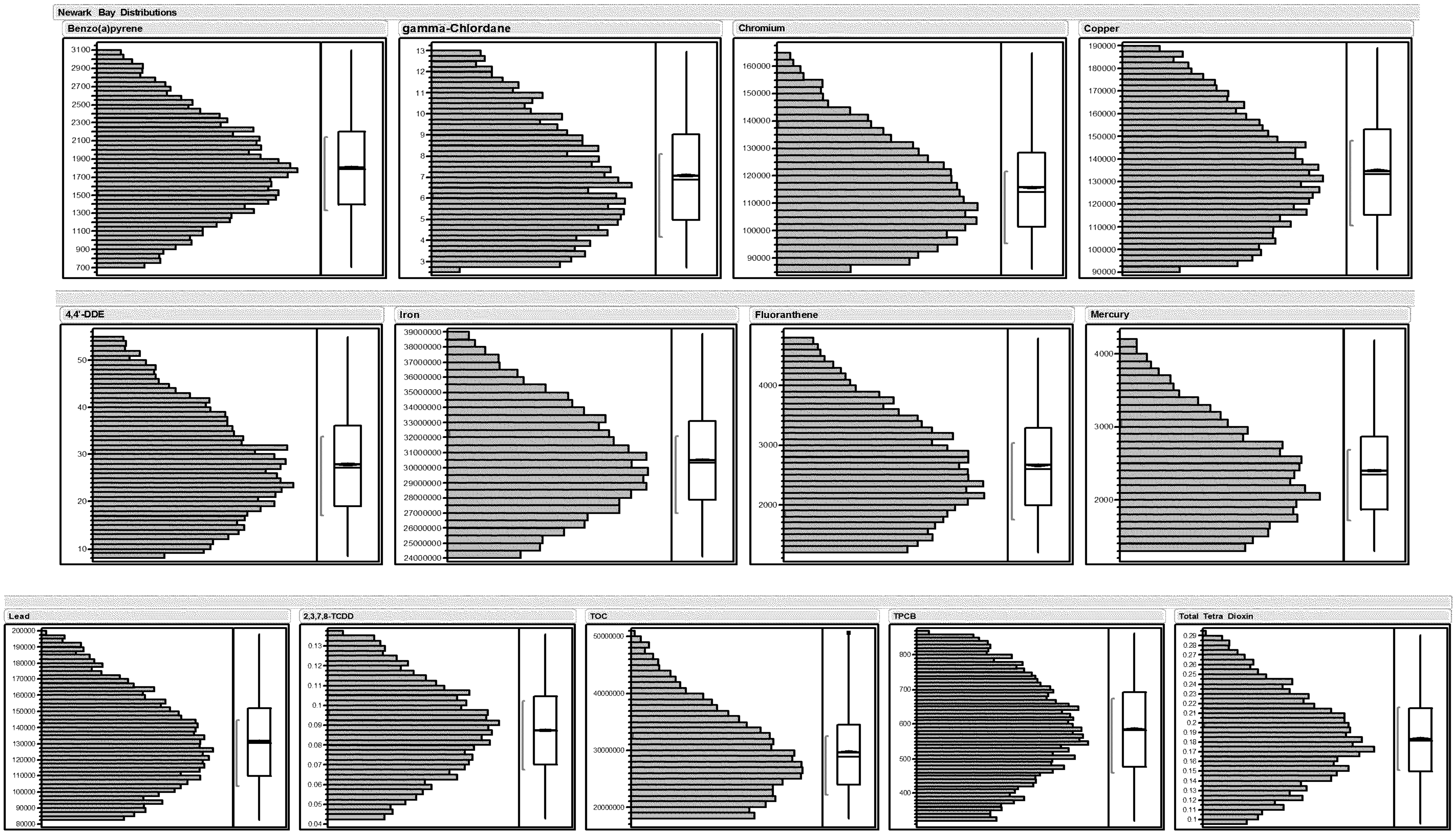
Lower Eight Miles of the Lower Passaic River

Figure A-1

2014



Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for Lower Passaic River (Receptor) Assuming Bounded Normal Distributions *Lower Eight Miles of the Lower Passaic River*	Figure A-2a 2014

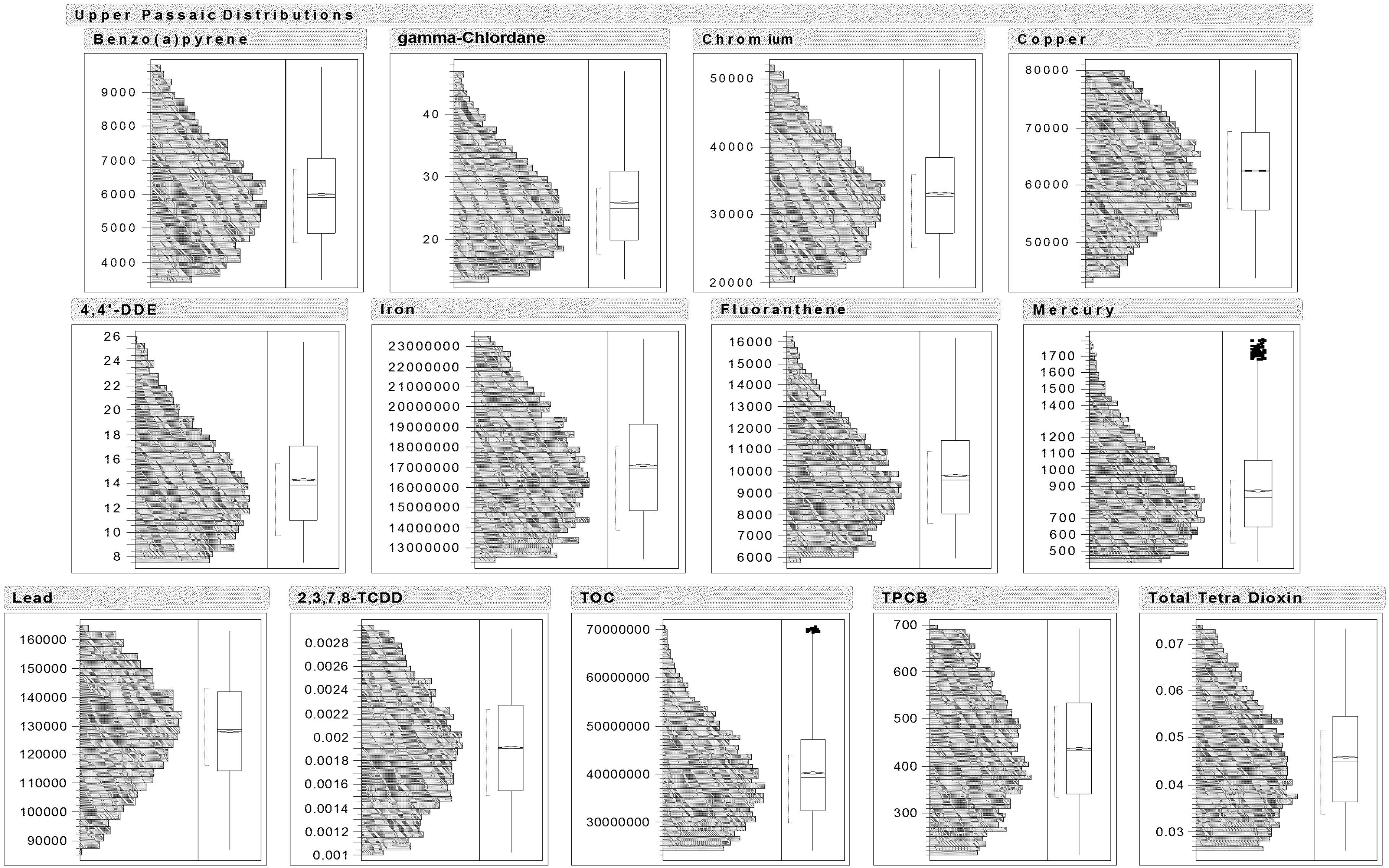


Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for Newark Bay Assuming Bounded Normal Distributions

Lower Eight Miles of the Lower Passaic River

Figure A-2b

2014

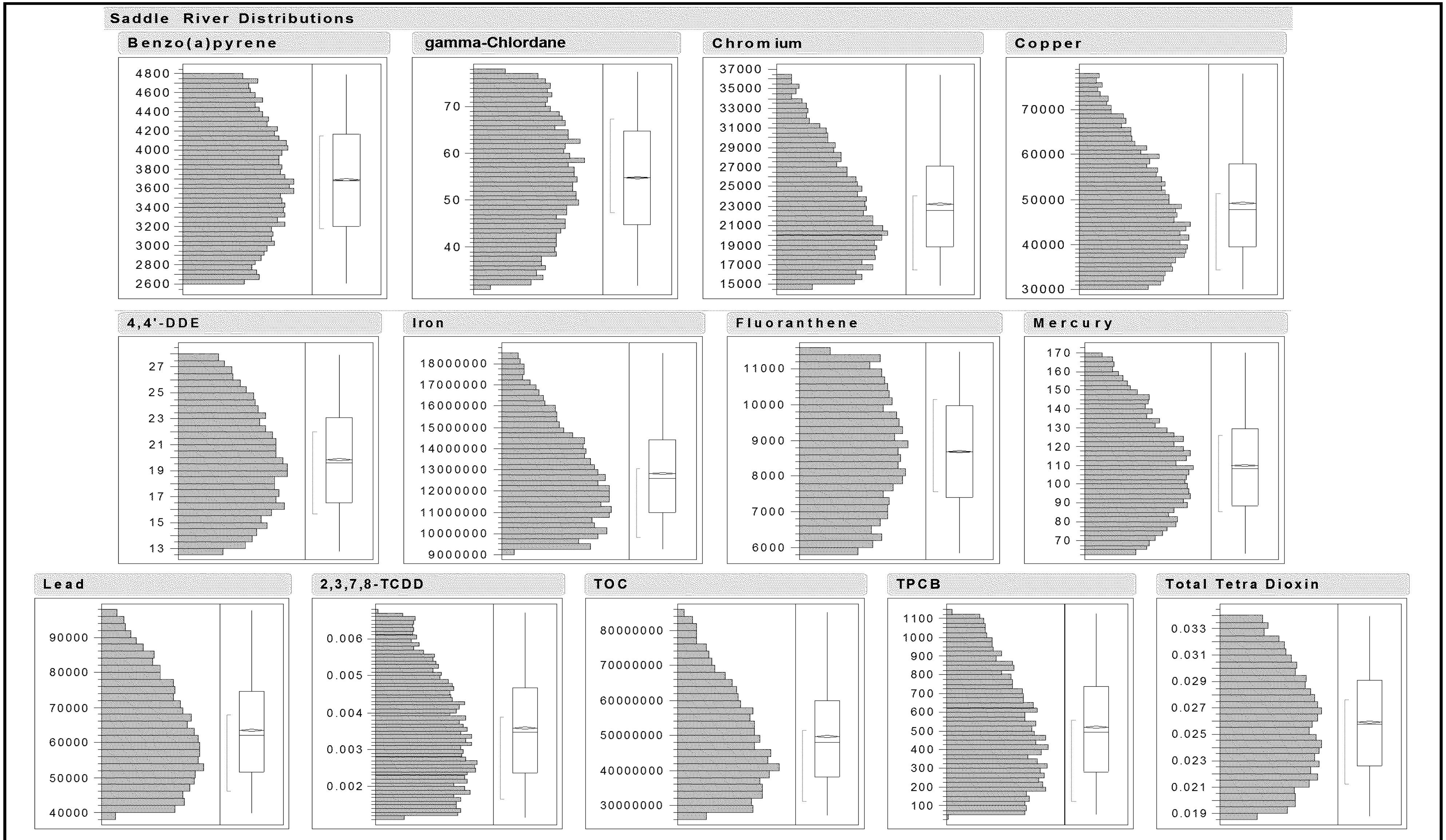


Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for Upper Passaic River Assuming Bounded Normal Distributions

Lower Eight Miles of the Lower Passaic River

Figure A-2c

2014

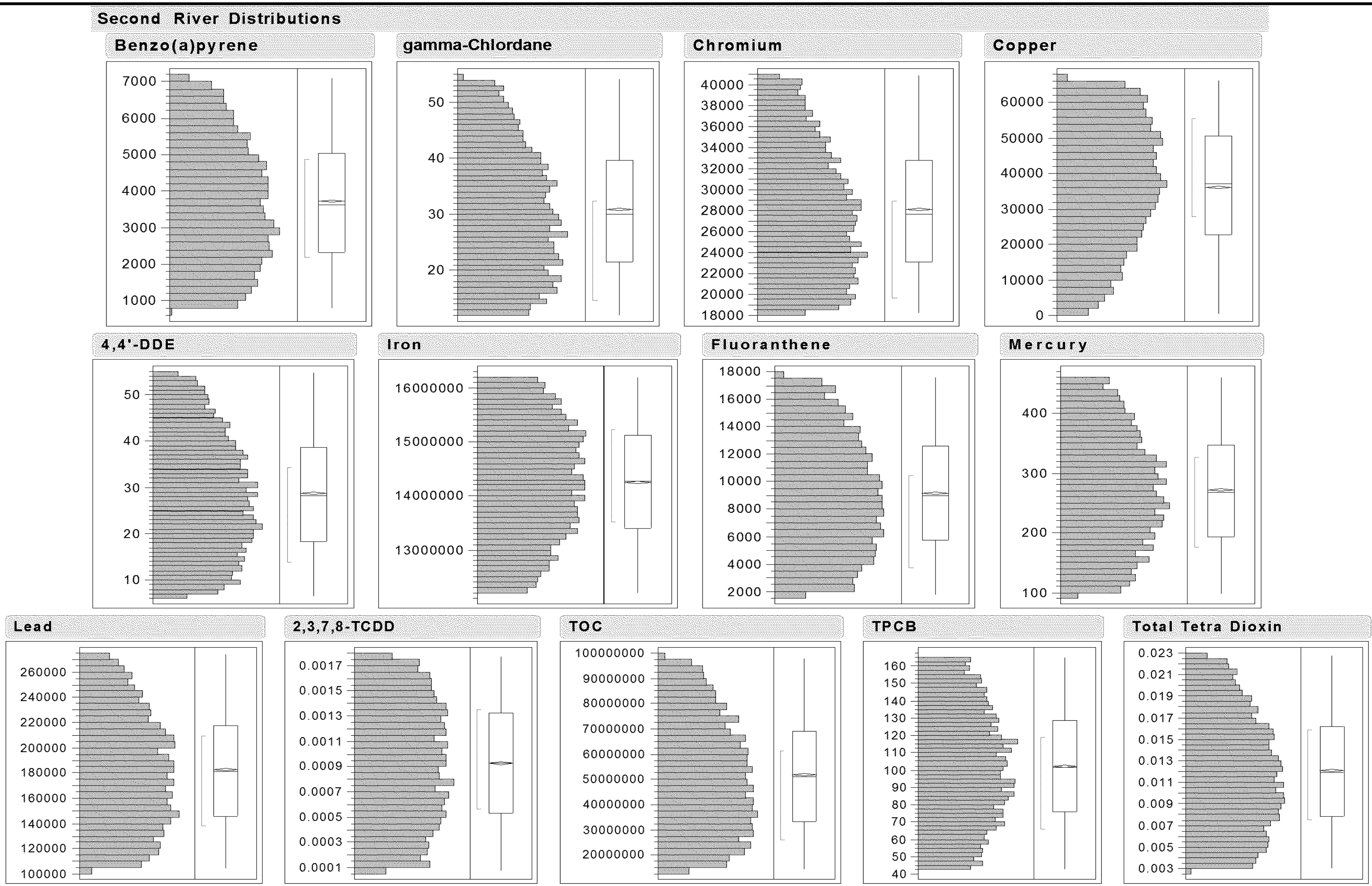


Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for Saddle River Assuming Bounded Normal Distributions

Lower Eight Miles of the Lower Passaic River

Figure A-2d

2014

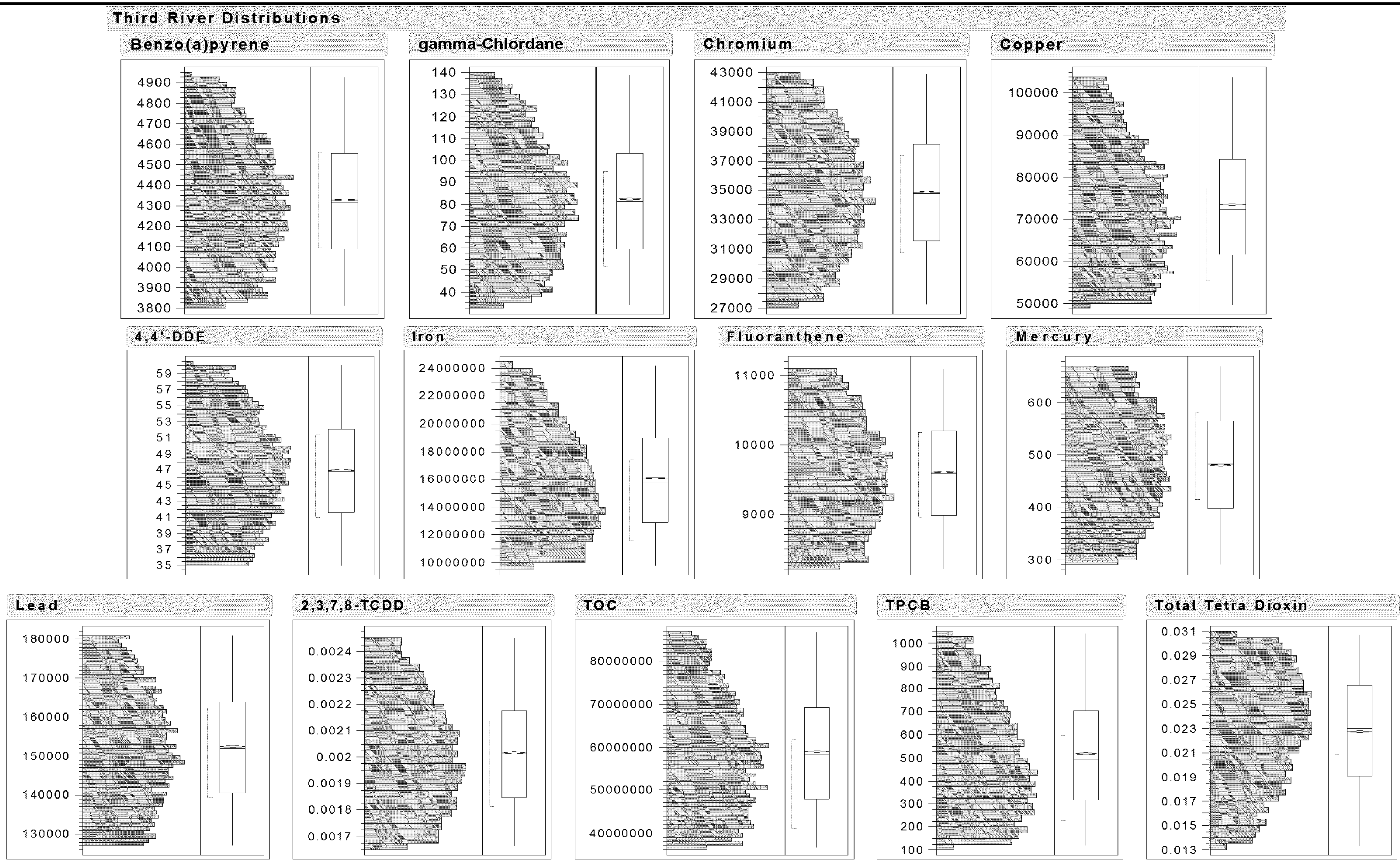


Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for Second River Assuming Bounded Normal Distributions

Lower Eight Miles of the Lower Passaic River

Figure A-2e

2014

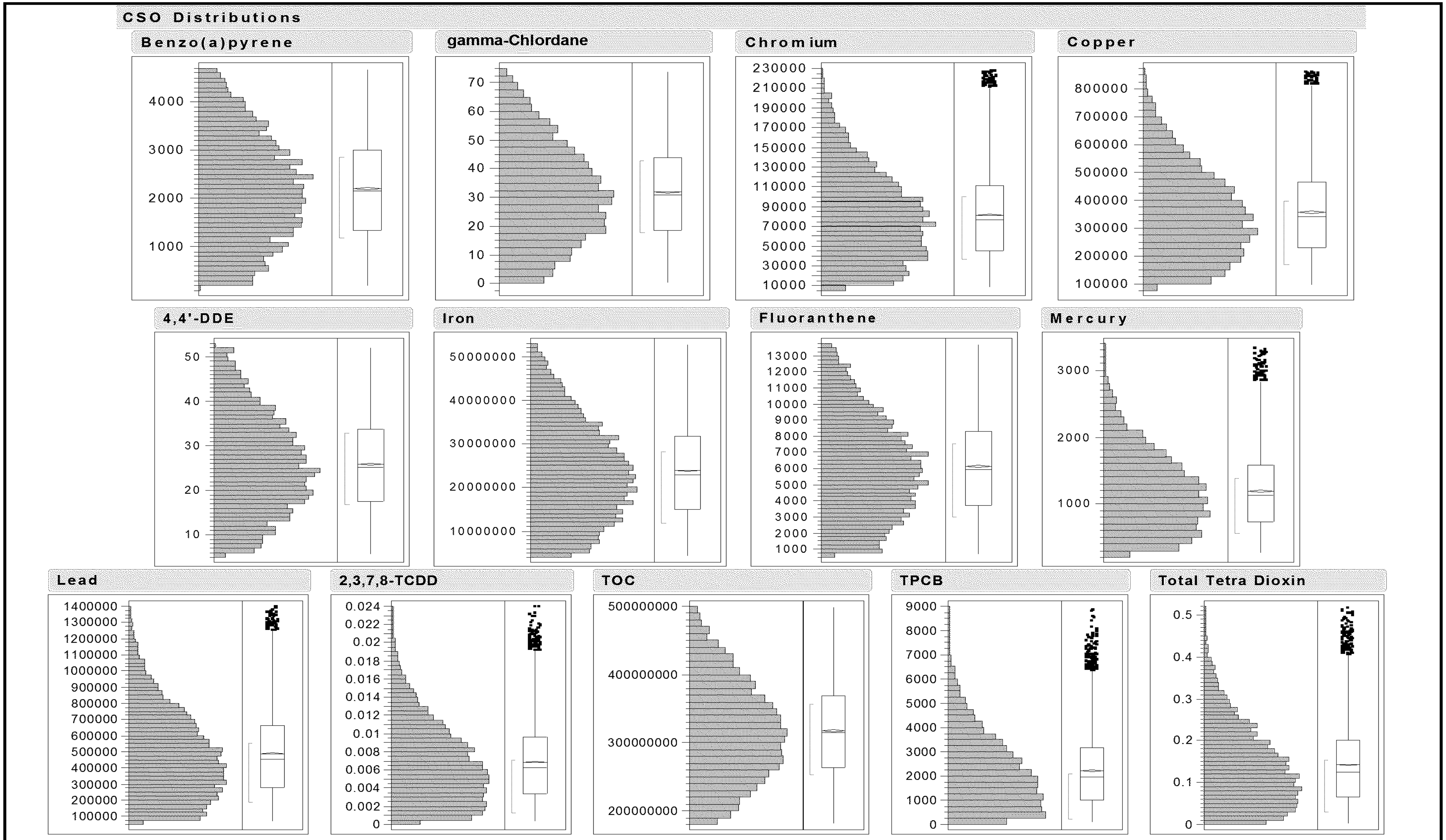


Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for Third River Assuming Bounded Normal Distributions

Lower Eight Miles of the Lower Passaic River

Figure A-2f

2014

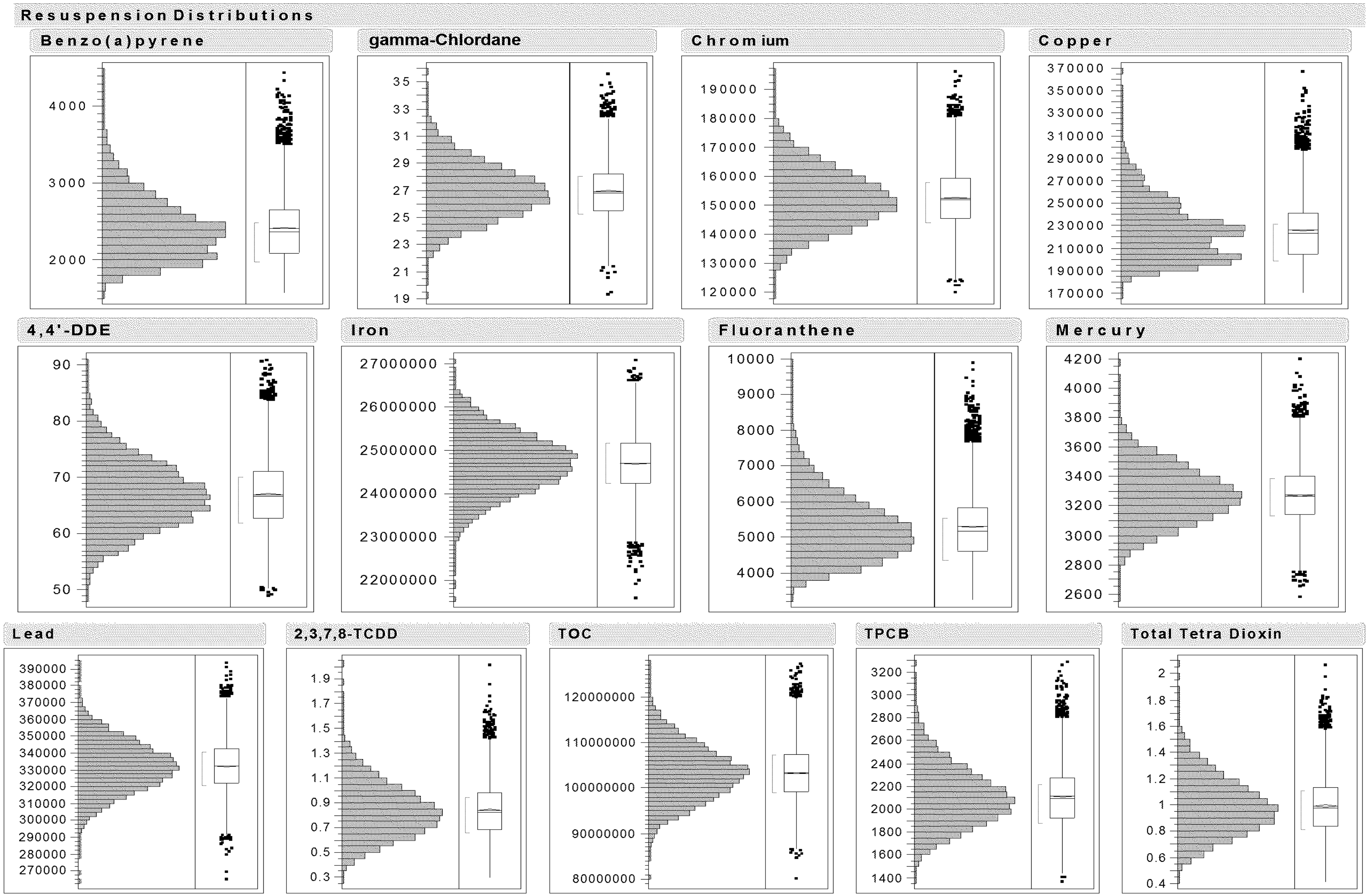


Monte Carlo Simulation of 10,000 Iterations of Chemical Profile for CSO Assuming Bounded Normal Distributions

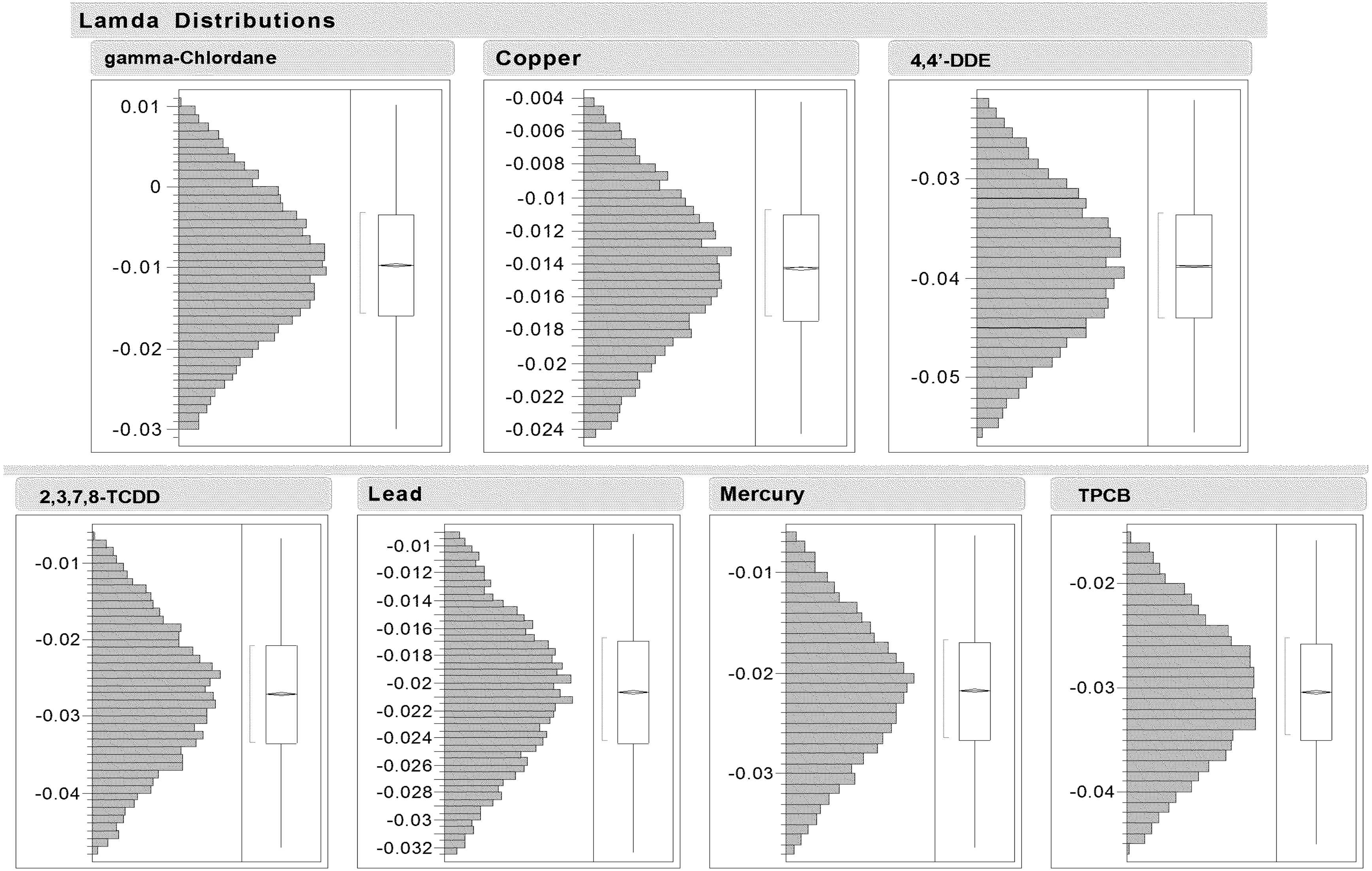
Lower Eight Miles of the Lower Passaic River

Figure A-2g

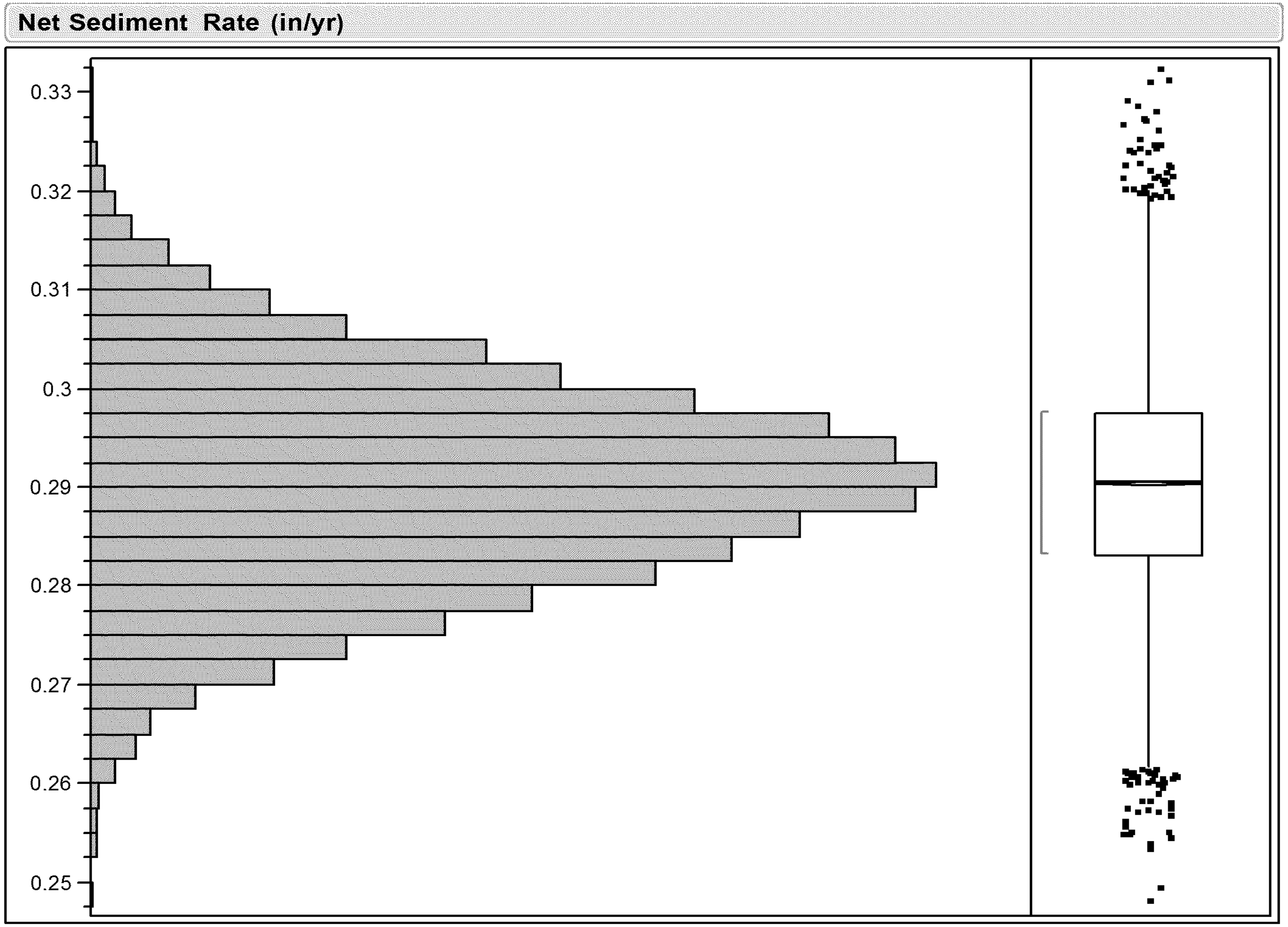
2014



	Bootstrap Simulation of 10,000 Iterations of Chemical Profile for Resuspension Source Based on 1995 TSI 0-6 inch Data (TSI Location 246 Excluded) *Lower Eight Miles of the Lower Passaic River*	Figure A-2h 2014



	Monte Carlo Simulation of 10,000 Iterations of Decay of Excess Sediment Contamination () Assuming Bounded Normal Distribution *Lower Eight Miles of the Lower Passaic River*	Figure A-3 2014

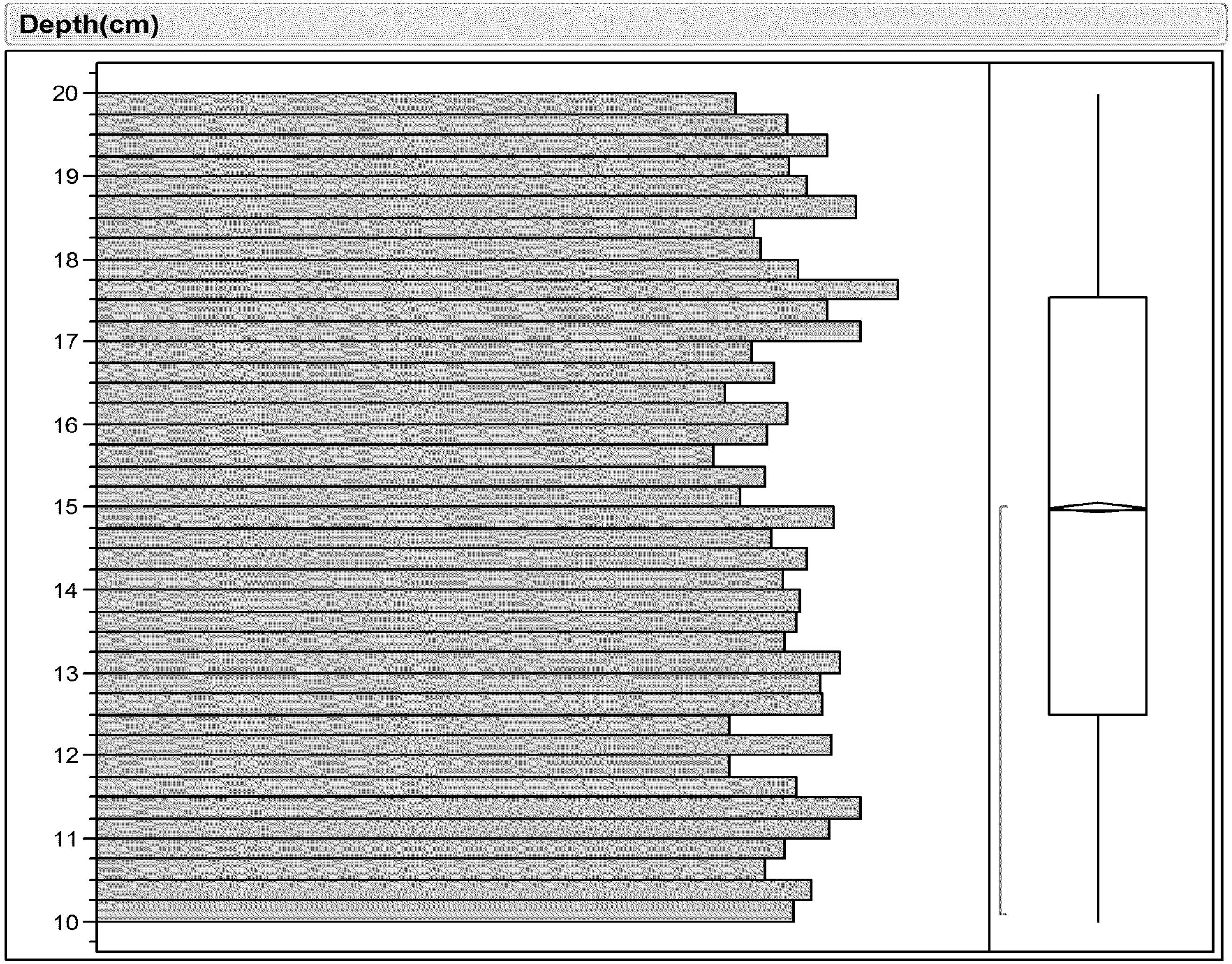


Bootstrap Simulation of 10,000 Iterations of Net Sediment Rate Based on the Differences Between the 1989 and 2007 Bathymetric Surfaces

Lower Eight Miles of the Lower Passaic River

Figure A-4

2014



Simulation of 10,000 Depth of Mixed Layer Based on Random Variation Between 10 and 20 cm

Lower Eight Miles of the Lower Passaic River

Figure A-5

2014

ATTACHMENT B

ESTIMATING THE COMMON HALF TIME FOR LEGACY SEDIMENTS IN LOWER PASSAIC RIVER

Attachment B: Estimating the Common Half Time for Legacy Sediments in Lower Passaic River.

1.0 Summary

A first-order regression model was applied to the excess chemical concentrations [1] and estimated time of deposition in the Lower Passaic River in order to determine a common half-time for legacy contaminated sediments. The data used in the model came from high resolution cores collected in the Lower Passaic River, and concentrations observed for the external sources. The chemicals included in the model were: gamma-Chlordane, 2,3,7,8-TCDD, Total PCB, 4,4'-DDE, mercury, lead, and copper. The results of the analysis indicate a common decay process [2] for these sediments at an average half time of approximately 35 years. The 95 percent confidence interval for this common half time is from 27 to 48 years. Although only seven chemicals were included in the model, this result also applies to other particle reactive contaminants in the Lower Passaic River that have a significant resuspension source term.

2.0 Objectives

- Determine whether the chemical specific decay rates or half times on the excess concentrations are similar (*i.e.,* no significant difference amongst them).
- Estimate the common decay rate for the excess concentrations in legacy sediment in the Lower Passaic River, along with the associated confidence interval.

3.0 Methods

- The chemicals included in the analysis were: gamma-Chlordane, 2,3,7,8-TCDD, Total PCB, 4,4'-DDE, mercury, lead, and copper.
- High-resolution core and external source data were used in the analysis. For the high resolution cores, data were limited to segments with approximate years from 1980 to 2007.
- A multiple-regression analysis was conducted to determine the similarities and differences amongst the half times of the various chemicals. This model combined the excess concentrations and time of deposition for all the chemicals. In addition, it included indicator variables for the chemical type and allowed for interaction effects between deposition time and chemical type. The first-order regression model used was:

[1] Excess chemical concentrations were defined as the Lower Passaic River sediment concentrations less the concentrations from the external sources.

[2] The term decay is used here to quantify the net processes that result in the decline of chemical concentrations over time as observed in the high resolution cores.

$\log_e ExC_i = \beta_0 + \beta_1 T_i + \beta_2 Chl_{i,} + \beta_3 PCB_i + \beta_4 DDE_i + \beta_5 Hg_i + \beta_6 Cu_i + \beta_7 Pb_i + \beta_8 T_i Chl_i + \beta_9 T_i PCB_i + \beta_{10} T_i DDE_i + \beta_{11} T_i Hg_i + \beta_{12} T_i Cu_i + \beta_{13} T_i Pb_i + \varepsilon_i$

Where:

$\log_e ExC_i$ = natural logarithm of the excess chemical concentrations (*i.e.,* high resolution core concentrations less external levels from head of tide, tributaries and CSO/SWOs).

$\beta_0 ... \beta_{13}$ = regression coefficients.

T_i = estimated deposition time from high resolution core dating.

Chl_i = indicator variable = 1 if chemical is gamma-Chlordane, 0 otherwise.

PCB_i = indicator variable = 1 if chemical is Total PCB, 0 otherwise.

DDE_i = indicator variable = 1 if chemical is 4,4'-DDE, 0 otherwise.

Hg_i = indicator variable = 1 if chemical is mercury, 0 otherwise.

Cu_i = indicator variable = 1 if chemical is cupper, 0 otherwise.

Pb_i = indicator variable = 1 if chemical is lead, 0 otherwise.

$T_i Chl_i$, $T_i PCB_i$, $T_i DDE_i$, $T_i Hg_i$, $T_i Cu_i$, $T_i Pb_i$ = interactions effects between time of deposition and chemical type.

Although there are seven chemicals, only six indicators were included (the indicator variable for 2,3,7,8-TCDD was not included). In the statistical theory of qualitative predictor variables, a qualitative variable of "c" classes is always represented by "c-1" indicator variables to avoid computational difficulties. In this application, the regression for 2,3,7,8-TCDD can be represented by all other indicator values being equal to zero. Note that the exclusion of the 2,3,7,8-TCDD does not affect model results. If the indicator variable of any the other chemicals modeled was excluded, the same regression results will be obtained.

- If the regression coefficients of the interaction terms are not statistically significant, then it can be concluded that the regression lines between natural logarithm of excess concentrations versus time for the individual chemicals are parallel, and that a common decay process occurs.

4.0 Results

Table B-1 presents the regression output for the first order model described above. A statistically significant model was obtained ($p < 0.001$ from Analysis of Variance results). The most important finding from this regression analysis is that the interaction terms are not significant ($p > 0.05$). Therefore, the individual chemical regressions are parallel and there is a common decay process for the legacy contaminated sediments in the Lower Passaic River. This legacy sediment represents the resuspension source that is the dominant contribution for most chemicals. Note that the residuals of this regression satisfy the regression assumptions of normality and homogeneity of variance.

Given that a common decay process exist for the Lower Passaic River excess legacy chemical concentrations, a second regression run was conducted to estimate the common decay rate and corresponding half time. For this regression run, the interaction terms which are not statistically significant were dropped from the regression equation. Table B-2 and Figure B-1 present the results for this reduced regression output. This reduced model and all the regression coefficients are statistically significant ($p < 0.0001$), and the chemical specific regressions lines are approximately parallel. The residuals of this reduced regression satisfy the regression assumptions of normality and homogeneity of variance. The regression coefficient for the time of deposition (β_1) under the reduced regression model, which represents the common decay rate is -0.02 (Table B-2). This common decay rate corresponds to a half time of approximately 35 years. Using the standard error and t-values from Table B-2 for β_1, the 95 percent confidence interval for β_1 is -0.026 to -0.014. The corresponding common half time confidence interval is 27 to 48 years.

Table B-1: Regression results with interaction terms

Multiple Regression Analysis

Dependent variable: LN_C

Parameter	Estimate	Standard Error	T Statistic	P-Value
CONSTANT	52.9204	16.7403	3.16126	0.0017
T	-0.0270905	0.00838435	-3.23107	0.0014
Chlo	-35.7128	23.5131	-1.51885	0.1299
Hg	-12.2543	21.4993	-0.569985	0.5692
DDE	23.2896	24.151	0.964335	0.3357
Pb	-12.8332	21.4993	-0.596913	0.5511
Cu	-23.8338	21.4993	-1.10858	0.2686
PCB	7.29054	23.5131	0.310063	0.7567
T_Chlo	0.0200792	0.0117754	1.70518	0.0893
T_Hg	0.00696226	0.0107712	0.646376	0.5186
T_DDE	-0.00903859	0.0120967	-0.747197	0.4556
T_Pb	0.00957072	0.0107712	0.888546	0.3750
T_Cu	0.0149399	0.0107712	1.38702	0.1666
T_PCB	0.000407156	0.0117754	0.0345769	0.9724

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1834.02	13	141.078	978.15	0.0000
Residual	39.663	275	0.144229		
Total (Corr.)	1873.68	288			

R-squared = 97.8832 percent
R-squared (adjusted for d.f.) = 97.7831 percent
Standard Error of Est. = 0.379775
Mean absolute error = 0.283226

Table B-2: Regression results without interaction terms

Multiple Regression Analysis

Dependent variable: LN_C

Parameter	Estimate	Standard Error	T Statistic	P-Value
CONSTANT	38.7251	5.7386	6.74818	0.0000
T	-0.0199807	0.002874	-6.95222	0.0000
Chlo	4.38214	0.0919774	47.6436	0.0000
Hg	1.64672	0.0857078	19.2132	0.0000
DDE	5.24658	0.0932575	56.2591	0.0000
Pb	6.27178	0.0857078	73.1763	0.0000
Cu	5.98301	0.0857078	69.8071	0.0000
PCB	8.1009	0.0919774	88.0748	0.0000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1832.76	7	261.822	1797.79	0.0000
Residual	40.9236	281	0.145636		
Total (Corr.)	1873.68	288			

R-squared = 97.8159 percent
R-squared (adjusted for d.f.) = 97.7615 percent
Standard Error of Est. = 0.381622
Mean absolute error = 0.283729

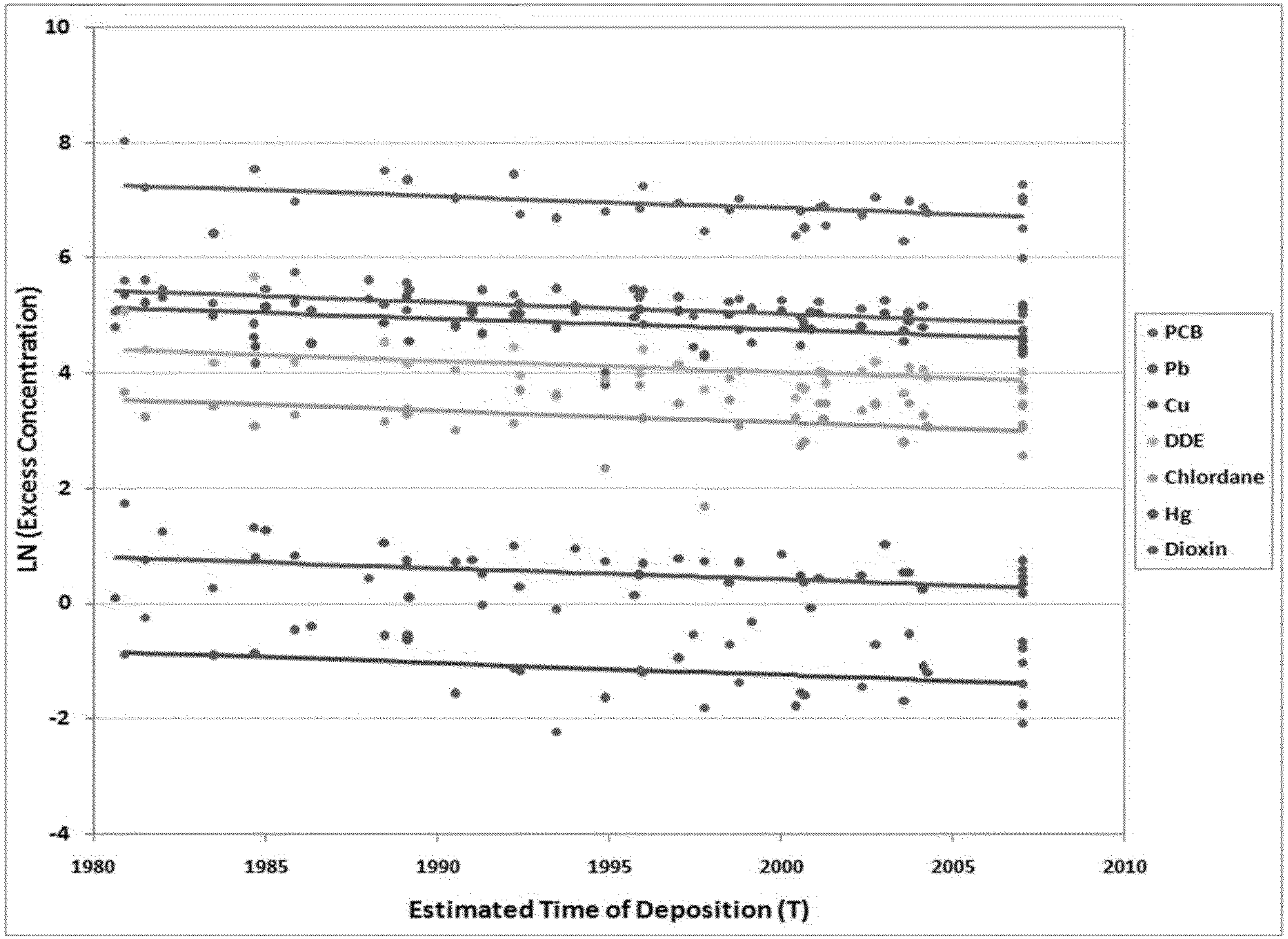


Illustration of natural logarithm of observed excess chemical concentration, time of deposition and fitted Regression Function *Lower Eight Miles of the Lower Passaic River*	Figure B-1 2014

ATTACHMENT C

DERIVATION OF THE TRAJECTORIES

Attachment C: Derivation of the Trajectories

The EMB model and the trajectory calculations are based on the assumption that the contaminant load in the Lower Passaic River is carried to the river on the incoming suspended sediment and that the masses contributed by each source are additive. Based on this assumption, we can develop a mass balance equation for each contaminant like Equation C-1.

$$C_T S_T = C_{RSP} S_{RSP} + C_{NB} S_{NB} + C_{DD} S_{DD} + C_{SR} S_{SR} + C_{3R} S_{3R} + C_{2R} S_{2R} + C_{CSO} S_{CSO} \qquad \text{Equation C-1}$$

where

C_T = contaminant concentration on recently deposited sediment (Be-7 bearing)
C_{RSP} = contaminant concentration on resuspended sediment within the Lower Passaic River
C_{NB} = contaminant concentration on sediment entering from Newark Bay
C_{DD} = contaminant concentration on sediment entering over Dundee Dam (from the Upper Passaic River)
C_{SR} = contaminant concentration on sediment entering from Saddle River
C_{3R} = contaminant concentration on sediment entering from Third River
C_{2R} = contaminant concentration on sediment entering from Second River and SWOs
C_{CSO} = contaminant concentration on sediment entering from CSOs
S_T = total solids load in the Lower Passaic River
S_{RSP} = total solids load from resuspension within the Lower Passaic River
S_{NB} = total solids load delivered from Newark Bay
S_{DD} = total solids load delivered over Dundee Dam (from the Upper Passaic River)
S_{SR} = total solids load delivered from Saddle River
S_{3R} = total solids load delivered from Third River
S_{2R} = total solids load delivered from Second River and SWOs
S_{CSO} = total solids load delivered from CSOs

If we define f_i as the fraction of the total solids load in the Lower Passaic River originating with source, i, we can rewrite Equation C-1 as follows:

$$C_{LPR} = C_{RSP} f_{RSP} + C_{NB} f_{NB} + C_{DD} f_{DD} + C_{SR} f_{SR} + C_{3R} f_{3R} + C_{2R} f_{2R} + C_{CSO} f_{CSO} \qquad \text{Equation C-2}$$

where

C_{LPR} = concentration of recently deposited sediment in the Lower Passaic River
f_{RSP} = fraction of the Lower Passaic River solids load originating as resuspension within the river
f_{NB} = fraction of the Lower Passaic River solids load originating in Newark Bay
f_{DD} = fraction of the Lower Passaic River solids load originating in the Upper Passaic River
f_{SR} = fraction of the Lower Passaic River solids load originating in the Saddle River

f_{3R} = fraction of the Lower Passaic River solids load originating in the Third River

f_{2R} = fraction of the Lower Passaic River solids load originating in the Second River or the SWOs

f_{CSO} = fraction of the Lower Passaic River solids load originating in the CSOs

The purpose of the EMB model was to find the best set of fractions for each of the solids sources to balance Equation C-2 for all of the contaminants of concern. The mechanics of the EMB model and the model results are described in more detail in Appendix F of the FFS. Table C-1 below shows the resulting fractions for each source based on the best solution to Equation C-2.

Table C-1: EMB Results – Fractional Contributions of Solids from each Source

Solids source	Percent contribution
Resuspension	47.8%
Newark Bay	13.5%
Upper Passaic River	32.3%
Saddle River	3.6%
Third River	0.5%
Second River and SWOs	1.3%
CSOs	0.3%

In order to project the contaminant concentrations in the river (C_{LPR}), we need to examine the past behavior of each component of the contaminant loads. In order to avoid including any effects of turning off sources, we will only examine the contaminant histories back to 1980.

There is no data available to quantify the past behavior of any of the tributaries or the CSOs and SWOs. Since these sources represent less than 5 percent of the total solids load, they cannot represent a significant portion of any contaminant load. Thus, their future trajectories are not important to this process and we will assume they are constant.

An understanding of the past behavior of sediment concentrations in the Upper Passaic River is based on a single high-resolution core from Dundee Lake, which was extracted by scientists at Renssalaer Polytechnic Institute (RPI) and analyzed by the USEPA. This core is described in more detail in Data Evaluation Report No. 3 - Contaminant History as Recorded in the Sediments in Appendix A. For all of the contaminants to be projected except HMW PAHs, the Dundee Lake sediments generally decreased in concentration from 1980 to about 1985 or 1990. After 1990 all contaminants (except HMW PAHs) are generally constant. We can use this information to project the Upper Passaic River component into the future as a constant source. For HMW PAHs, the concentrations seem to decrease from 1980 to the mid 1990s and then they begin to increase. That increase may continue in the future, but for the purposes of this analysis, we will assume a constant concentration from 2005 into the future. This means that the trajectory analysis may be under-predicting the HMW PAHs concentrations in the future.

The Upper Passaic River component of the Lower Passaic River sediments is not assumed to have been constant in the past, however. The data points from the RPI Core were linearly interpolated to provide a concentration for each year from 1980 to 2005 and the actual measured values were used in the analysis.

Newark Bay and the resuspension term are both assumed to be declining, but without any specific information on either source, they cannot easily be separated. Therefore, both were assumed to decay exponentially with the same half time (time required for the concentration to drop by 50 percent). The half time was calculated by separating the constant sources and the Dundee Dam source from the total concentrations reported on the dated high resolution cores from the Lower Passaic River according to the following equation:

$$C_{EX} = C_{HRC} - C_{DD} f_{DD} - C_{SR} f_{SR} - C_{3R} f_{3R} - C_{2R} f_{2R} - C_{CSO} f_{CSO} \qquad \text{Equation C-3}$$

where

C_{EX} = "excess" concentration (originating from Newark Bay and resuspension)

C_{HRC} = concentration reported on the high resolution cores

The concentrations for the tributaries and the CSOs were based on averages from the measurements taken during the 2007/2008 sampling events. The concentration for the Upper Passaic River was based on a linear interpolation of data from the dated RPI core from Dundee Lake.

The resulting data was fit to an exponential decay curve, defined by Equation C-4.

$$C(t) = C_o e^{-\lambda t} \qquad \text{Equation C-4}$$

where

$C(t)$ = concentration at time, t

C_o = concentration at $t = 0$

λ = decay coefficient

t = time

The half time of the decay curve can be calculated from the decay coefficient as shown in Equation C-5.

$$t_{1/2} = \frac{\ln\left(1/2\right)}{\lambda} \qquad \text{Equation C-5}$$

where

$t_{1/2}$ = half time for the exponential decay curve

The next step is to calculate the concentrations of sediments from each source into the future. For the constant sources (tributaries and SWOs) and the Upper Passaic River, this is easy. These sources are assigned the average concentration from recent sediment samples from 2005 throughout the length of the trajectory. Newark Bay and resuspension contributions must be calculated using the decay rate defined above.

Equation C-4 shows that the limit of the concentration as time approaches infinity is zero. Although we are assuming an exponential decay for Newark Bay, we do not expect the Newark Bay sediment concentrations to reach zero. The EMB model used the northern samples from Newark Bay as the end members. Most contaminants show an increasing trend in concentration from the south to the north end of the bay, probably indicating mixing with Passaic River sediments. For this analysis, we assume that the Newark Bay sediments will never drop below the level recently measured in the southern samples in Newark Bay. This floor value is implemented as shown in Equation C-5, which forces the concentration to approach C_{Floor} as time approaches infinity.

$$C_{NB}(t) = \left[C_{NB}(2005) - C_{Floor}\right]e^{-\lambda(t-2005)} + C_{Floor} \qquad \text{Equation C-5}$$

where

C_{Floor} = minimum concentration on Newark Bay sediments as defined by southern samples

There is also a floor value associated with the resuspended sediment concentrations. Because the resuspending sediment is actually the reworking of old sediment, its concentration cannot drop beneath a floor which is defined as the sum of all other sources. Equation C-6 shows the calculation of the floor for any contaminant. The southern Newark Bay sediments were again used to define the Newark Bay contribution.

$$C_{Floor} = \frac{C_{NB}f_{NB} + C_{DD}f_{DD} + C_{SR}f_{SR} + C_{3R}f_{3R} + C_{2R}f_{2R} + C_{CSO}f_{CSO}}{f_{NB} + f_{DD} + f_{SR} + f_{3R} + f_{2R} + f_{CSO}} \qquad \text{Equation C-6}$$

where

C_{Floor} = minimum concentration on resuspended sediments

Similar to Equation C-5, the resuspension concentration was calculated using Equation C-7. The 2005 concentration, $C_{RSP}(2005)$ was assigned based on the average concentration measured in the 1995 TSI surface samples.

$$C_{RSP}(t) = \left[C_{RSP}(2005) - C_{Floor}\right]e^{-\lambda(t-2005)} + C_{Floor} \qquad \text{Equation C-7}$$

where

C_{Floor} = minimum concentration on resuspended sediments as defined in Equation C-6

When all of the components had been projected into the future, Equation C-2 was used to sum them up and predict the future concentration and construct the No Action (Alternative 1) trajectory.

Constructing trajectories for the remediation options (Alternatives 2, 3 and 4) involved more manipulations of the data. We can simplify Equation C-2 to Equation C-8 by defining:

$$\sum C_i f_i = C_{NB} f_{NB} + C_{DD} f_{DD} + C_{SR} f_{SR} + C_{3R} f_{3R} + C_{2R} f_{2R} + C_{CSO} f_{CSO}$$

$$C_{LPR} = C_{RSP} f_{RSP} + \sum C_i f_i$$

Equation C-8

Because the volume of solids contributed by resuspension and the characteristics of those solids change with remediation, we define the remediated concentration of surface sediments in the Lower Passaic River using Equation C-9.

$$C_{REM} = C'_{RSP} f'_{RSP} + \sum C_i f'_i$$

Equation C-9

where

C_{REM} = Lower Passaic River surface concentrations after remediation
C'_{RSP} = contaminant concentration on resuspended sediments after remediation
f'_{RSP} = fraction of solids originating as resuspension after remediation
f'_i = fraction of solids originating with source, *i*, after remediation

Using the definition of *f*, we can convert Equation C-9 to Equation C-10.

$$C_{REM} = \frac{C'_{RSP} S'_{RSP}}{S'_T} + \frac{\sum C_i S_i}{S'_T}$$

Equation C-10

where

S'_{RSP} = solids load contributed from resuspension after remediation
S_i = solids load contributed from source, *i*
S'_T = solids load in the Lower Passaic River after remediation

We define the following variables:

a = the unremediated fraction of the erosional silt areas of the river bed
b = the remediated fraction of the erosional silt areas of the river bed
a = *1-b*
c = the amount of resuspension occurring in the remediated areas per unit area as a fraction of the resuspension occurring in unremediated areas per unit area

Using these definitions, we can define the solids load from resuspension after remediation according to Equation C-11.

$$S'_{RSP} = S_{RSP}(a) + S_{RSP}(b)(c)$$

Equation C-11

The first term on the right-hand side of the equation represents the resuspension occurring in the unremediated areas of the river, while the second term includes the resuspension occurring in the remediated areas of the river. This equation can be simplified to Equation C-12.

$$S'_{RSP} = S_{RSP}\left(1 - b\left(1 - c\right)\right) \qquad \text{Equation C-12}$$

The total solids load in the river after remediation can be defined by Equation C-13.

$$S'_T = S_T - S_{RSP} + S'_{RSP} \qquad \text{Equation C-13}$$

By plugging Equation C-13 into Equation C-12 and simplifying, we get Equation C-14.

$$S'_T = S_T - S_{RSP}\left(b\right)\left(1 - c\right) \qquad \text{Equation C-14}$$

We can simplify Equation C-14 further by using the definition for f_{RSP}.

$$S'_T = S_T - \left[S_{RSP}\left(b\right)\left(1 - c\right)\right]\frac{S_T}{S_T}$$

$$S'_T = S_T\left(1 - f_{RSP}\left(b\right)\left(1 - c\right)\right) \qquad \text{Equation C-15}$$

The concentration of the resuspending sediment after remediation is defined by Equation C-16.

$$C'_{RSP} = \frac{C_{RSP}\left(a\right) + C_{cap}\left(b\right)\left(c\right)}{a + bc} \qquad \text{Equation C-16}$$

where

C_{cap} = concentration of sediment resuspending from remediated areas

As described in Appendix C of the FFS and the Data Evaluation Reports, there is no appreciable dioxin contamination above RM12, so the fraction of solids eliminated by remediating is not the same as the fraction of dioxin mass isolated by remediating. To account for this issue, we define a new variable d as the difference between a and the fraction of dioxin mass isolated by remediating. For all other contaminants, d will remain zero. This addition to Equation C-16 yields Equation C-17.

$$C'_{RSP} = \frac{C_{RSP}\left(a - d\right) + C_{cap}\left(b\right)\left(c\right)}{a + bc} \qquad \text{Equation C-17}$$

where

d = the difference between the fraction of solids eliminated by remediating and the fraction of dioxin mass isolated by remediating

Equation C-17 reduces to Equation C-18 using the definition of a.

$$C'_{RSP} = \frac{C_{RSP}\left(1 - b - d\right) + C_{cap}\left(b\right)\left(c\right)}{1 - b\left(1 - c\right)} \qquad \text{Equation C-18}$$

The final equation for the remediated concentration of suspended sediment in the Lower Passaic River can then be developed by substituting Equations C-12, C-15 and C-18 into Equation C-10 as shown in Equation C-19.

$$C_{REM} = \frac{\left[\frac{C_{RSP}(1-b-d)+C_{cap}(b)(c)}{1-b(1-c)}\right]\left[S_{RSP}(1-b(1-c))\right]}{S_T\left(1-f_{RSP}(b)(1-c)\right)} + \frac{\sum C_i f_i}{S_T\left(1-f_{RSP}(b)(1-c)\right)} \qquad \text{Equation C-19}$$

Through additional simplification and remembering the definition of f_{RSP} and f_i, Equation C-19 can be converted to Equation C-20.

$$C_{REM} = \frac{f_{RSP}\left(C_{RSP}(1-b-d)+C_{cap}(b)(c)\right)}{1-f_{RSP}(b)(1-c)} + \frac{\sum C_i f_i}{1-f_{RSP}(b)(1-c)} \qquad \text{Equation C-20}$$

The calculation of C_{cap} is based on the assumption that there is a 6-inch biologically active zone that is well-mixed and available for resuspension. The average annual sedimentation rate was determined to be 0.27 inches. Based on this data, we can estimate that it takes 22 years to build up a 6-inch layer in the remediated area. C_{cap} can then be calculated by assuming 5.73 inches have the same concentration as C_{cap} the previous year and 0.27 inches have the same concentration as the newly deposited sediment (C_{REM}) the previous year. The two pieces are assumed to be completely mixed and C_{cap} can be calculated as shown in Equation C-21.

$$C_{cap(t)} = \frac{1}{22}\left[21C_{cap(t-1)} + C_{REM(t-1)}\right] \qquad \text{Equation C-21}$$

where.

Equation C-21 is also used to calculate the average concentration in the upper six inches [illegible] concentrations. [illegible] remediation, c is assumed to be zero since the cap or backfill will be made up of sand in unremediated areas per unit area. During remediation, resuspension is assumed to particles too large to be suspended under normal hydrodynamic conditions. However, as decline linearly until remediation is complete. For Alternatives 2 and 3, immediately after of 0.27 inches, this point will be reached 22 years after remediation. For simplicity, the value of c is assumed to move linearly from a value of zero just after remediation is complete (*i.e.,* 2029 for Alternative 2, 2022 for Alternative 3) to a value of one in the year 2051 for Alternative 2 and 2044 for Alternative 3.

For Alternative 4, the mixing described in Equation C-21 is also used to calculate the concentration in the upper 6-inch biologically active zone for the unremediated areas below RM8.3. The area averaged concentration across both remediated and unremediated areas was then calculated by assuming one-third of the area below RM8.3 was remediated.